The Thesis Committee for Alexander William Marden
Certifies that this is the approved version of the following Thesis:

Interactions and influences of savanna fire across multiple extents

APPROVED BY
SUPERVISING COMMITTEE:

Kelley A. Crews Meyer, Supervisor

Jennifer A. Miller

Kenneth R. Young

Interactions and influences of savanna fire across multiple extents

by

Alexander William Marden

Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Arts

The University of Texas at Austin

December 2018

Acknowledgments

First, thank you to my advisor Kelley Crews Meyer for providing countless amounts of support, feedback, and encouragement during the past two years, and to Thoralf Meyer for being a constant source of knowledge in the classroom, the lab, and Botswana. Also thank you to Thomas Christiansen for all of the mentoring, driving, and sharing of expertise in the field.

Thank you to my committee members Jennifer Miller and Kenneth Young for all of the feedback and inspiration.

To everyone else in the DLL–Amelia, Brendan, Dan, Fransisco, and Robert–along with the rest of the UT geography graduate community, thank you for the advice, company, and good vibes shared across many coffee breaks and happy hours.

Thanks to The Department of Geography and the Environment at the University of Texas for the Veselka grant that helped fund my fieldwork.

I am so grateful for my girlfriend Jordan, you have been my biggest supporter ever since you helped me with my high school math homework eight years ago.

And finally, thank you to my mom, dad, and sister who have given me so much and instilled a yearning to explore the unfamiliar that has led me to this point.

Interactions and influences of savanna fire across multiple extents

Alexander William Marden, M.A.
The University of Texas at Austin, 2019

Supervisor: Kelley A. Crews Meyer

The spatiotemporal interactions and feedbacks of fire and vegetation in savanna systems are a key component of savanna structure, function, and can give insight into woody plant encroachment. The increased accessibility to remote sensing data and software via Google Earth Engine for fire analysis facilitates integrated savanna assessments for local-to-regional analyses and management. This study assesses spatial and temporal fire dynamics in the Botswana Kalahari at different extents and resolutions to test the hypothesis that fire and vegetation patterns interact via distinct processes at different extents and resolutions in savanna systems. MODIS burn products (MCD64A1 500meters) and *in situ* vegetation and fire measurements were used to test the affects of variables at different extents and resolutions on savanna fire and vegetation patterns. Spatiotemporal analysis at the extent of the Botswana Kalahari explored 1) the spatial autocorrelation of fire return time using a bivariate Moran's I analysis to observe how large patterns of fuel dynamics affect

neighboring areas across time and space and 2) how variability of variables over small spaces influence larger patterns of fire occurrence using Geographically Weighted Regression or GWR. *In situ* grass and woody vegetation characteristics were measured and combined with MODIS fire history data to observe how vegetation at the square meter scale is influenced by regional affects of fire occurrence, grazing, and human influence using OLS regression. Fire intensity and post-fire vegetation mortality assessments were performed on sites that burned approximately two months after initial measurements were recorded to observe vegetation affects on fire intensity and the initial affects of fire on vegetation. Woody plant populations were projected across a number of fires under divergent fuel conditions to observe how fine resolution fire and vegetation patterns influence larger patterns.

In the Botswana Kalahari study area, fire occurrence over time was heavily affected by fire presence in neighboring 500m pixels (first and second order), an indication that spatiotemporal patterns of fire are affected by patterns in neighboring areas. The temporal and spatial patterns observed suggest that temporally dynamic neighboring fuel conditions impact fire in a given location.

Large scale patterns were observed between variables and fire occurrence using an OLS regression, and spatial variability of local coefficients was observed using a GWR model. Seasonality of precipitation, boreholes, and EVI had negative significant coefficients. Soil moisture, drought severity, and herbaceous cover had positive significant coefficients, but when examined locally using GWR there were high amounts of spatial variation – every variable ranged from positive to negative significant local coefficients except for seasonality of precipitation. Explanatory power of the variables was significantly improved by the GWR model. The variation in the local coefficients present from the GWR maps indicate that larger patterns of fire presence are influenced by locally specific contexts, while the relative consistency of coefficient sign and high coverage of significance of EVI and herbaceous cover variables signals that fuel conditions are important across the area.

The *In situ* OLS model showed that fire along with regional patterns of herbivory and human influence were highly impactful on grass biomass. Past fire presence was significant and highly correlated with grass biomass. Woody plant canopy cover and regionally specific anthropogenic influence via a road/river with an associated grazing intensity gradient had negative associations with grass biomass.

The *In situ* pre and post-burn vegetation measurements show that distinct fuel conditions caused fire intensity to vary dramatically over a small area on the same day, and the projected woody plant population model suggests that continued disparate fuel conditions would cause significantly different vegetation conditions. Post burn vegetation measurements indicated that the plot with high grass biomass and low woody biomass had high fire intensity while the plot with low grass biomass and high woody biomass had a low intensity fire. Long term modeling of the two fuel scenarios projected high amounts of woody plant growth with high recruitment and little mortality in the low fuel scenario, while the high fuel scenario projected a stable woody plant population. These findings support the idea that fine resolution variability of fire presence affects larger patterns of vegetation uniformity/non-uniformity.

Taken together, the findings suggest that different specific factors interact between extents and resolutions of fire patterns – land use at large extents affect fire presence in a given area, and fine resolution vegetation conditions affect directionality and spread of fire that influence larger patterns of fire. However, fuel connectivity is a common variable that connects these interactions, and since fuel conditions are affected by past fire presence and intensity, fire history is a common factor that is important across scales. With these interactions in mind, the observed vegetation heterogeneity in the study is likely caused in part by the diversity of land uses in the surrounding areas.

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Chapter 1

Introduction to fire and savanna dynamics

1.1 Introduction

The issue of scale is becoming more prominent as global scale remote sensing analyses are contributing to a growing number of large spatial and temporal scale studies that are difficult to compare to small scale, site-specific studies. There is a definite need in the literature for studies that seek to bridge these gaps through explicit explorations on 1) the effect of analysis scale on results of savanna ecology research, 2) the multiple scales of occurrence and function of the drivers, interactions, and feedbacks of fire in savannas, and 3) the ability of large scale analyses to inform small scale savanna management and the ability of small scale analyses to inform large scale savanna management and policy. The variety of spatial and temporal scales of functioning in savanna systems and the multitude of scales at which emergent patterns occur present a key issue in the understanding and maintenance of grass-tree dynamics.

Fire and grazing are often the focus of land managers charged with maintaining the tree-grass coexistence in savannas, particularly because managers are unable to easily control such variables as climate and competition between grass and trees (Venter et al., 2017). It is imperative that managers and policy makers understand how often an area should burn to retain grass-tree balance as well as the effect of grazing densities on fire and overall savanna structure and function. Fire and grazing operate at multiple spatial and temporal scales, and explicit approaches are needed to determine what types and scales of fire and grazing analyses are relevant to various policies and management decisions. This project investigates fire and grazing dynamics at country, regional, and local scales in Botswana – a country noted as lacking explicit findings relevant to fire and grazing dynamics – using a combination of remotely sensed and *in situ* methodologies at various scales to provide a multi-scale analysis.

1.2 Fire Dynamics

The presence of fire or lack thereof drives regional vegetation patterns of savanna landscapes and has cascading impacts on ecosystem function (Grady and Hoffmann, 2012; Touboul et al., 2018). Savanna systems are highly dynamic due to fluctuations in tree-grass competition. The presence and return of fire inhibits the spread of woody plant expansion in systems that are otherwise favorable to their dominance by limiting tree recruitment through burning of non-mature trees. In the absence of fire, one of the few limitations to tree density becomes tree to tree competition in the form of inter- and intra-specific species competition at the level of the population or community, not at the level of the ecosystem at which fire functions (Scholes and Archer 1997;

Sankaran et al., 2005). However, the opposite condition – highly frequent fires – may lead to grassland-like conditions because almost all woody species are eliminated by fire in the seedling stages year after year (Van Langevelde et al., 2003). Therefore, an established hypothesis is that savannas are dependent on an intermediate level of disturbance by fire.

The interactions between fire, moisture availability, and tree basal area constitute key dynamics between woody cover and fire relationships. A higher availability of moisture allows for the growth of more plant biomass in both woody and grass species. Concurrently, the increased grass biomass can serve as fuel for fires, leading to higher intensity fires and possibly more frequent fires (Laris, 2017). These linkages among moisture, biomass, and fire are present with woody species as well. Moisture availability determines a maximum value of woody biomass, and fire decreases woody biomass keeping woody biomass under a maximum value (Lehmann et al. 2014).

Given the control role that fire plays in savanna ecosystems and widespread anthropogenic fire suppression it seems likely that fire plays a strong global role in woody encroachment, although fire is significantly more heterogeneous across savanna systems than atmospheric CO2 so it may be more difficult to draw global scale conclusions about fire's effect on encroachment (Staver et al., 2011; Pausas and Ribeiro, 2017). Because of the heterogeneity of fires in savanna systems, a multi-scalar approach is needed to understand fire's role within savanna systems.

1.3 Fire and Herbivory

Burning to improve livestock and wildlife grazing conditions via reducing woody competition and encouraging "green up" in the form of new grasses is not a new management strategy. However, the precise fire regime that has historically been a part of ecosystems and that may result in the desired vegetation composition and pattern is difficult to predict in different areas under different conditions. The relationship between fire and grazing systems is therefore significant. Specifically, the relationship between the two can be described in terms of the interactions and feedbacks among grazing intensity, grass fuel amount, and fire frequency including suppression, exclusion, and prescribed burning from rangeland managers (Langevelde et al., 2003; D'Odorico et al., 2006; Wilcox et al., 2018). A main process affecting savanna grazing systems is pyric herbivory – the reduction of herbaceous cover and reduction of fuel, reducing herbaceous-woody plant competition and fire leading to encroachment of woody plants (Wilcox et al., 2018).

Land use plays an important role in patterns of fire occurence. Because pyric herbivory is influential in savanna dynamics, the existence and density of herbivory in a given area influences the fuel conditions, which determine how fire will burn (Wigley et al.,2010). Open rangelands have diverse fire patterns because a variety of herders and stakeholders tend to burn areas independently (Hudak et al., 2014). In closed ranches or rangelands and government specified protected areas managed by a single entity burning is usually more uniform because there is a single management strategy being employed (Wigley et al., 2009). Areas containing human populations and infrastructure tend not to burn, but surrounding areas may be prone to burning because of human ignition sources (Andela et al., 2017).

Roques and colleagues (2001) measured woody encroachment and tested the statistical significance of a number of drivers across 103 plots in north-eastern region of Swaziland across five different land-use areas. The study showed that from 1976-1997 across the study area, woody plant coverage increased from 2 percent to 31 percent. In the analysis, grazing had a strong negative impact on fire occurrence. The fire suppression effect from heavy grazing had the highest impact on woody plant encroachment. Drought frequency also highly affected the amount of woody encroachment. These drivers were influential at different magnitudes in different time periods: From 1971-1990 grazing/fire was the most important factor, while from 1990-1997 initial woody plant cover was the most important factor in predicting woody cover. In this second time period, the initial conditions had a higher influence on woody cover than the measured drivers. The study however did not focus on the influence of study extent and multiple scales of fire, herbivory, and vegetation interactions.

Such research has pointed to additional complexities in the dynamics between fire and grazing. Therefore, researchers have also investigated a vital, but easily overlooked component in savanna land management–the importance of burn conditions (Laris et al., 2017). Outside of the scientific literature specifically focused on fire ecology, the impact of fire is usually discussed in a presence/absence scenario (Luo et al., 2017). This characterization neglects a large amount of nuance that profoundly affects how systems react to fire. For example, empirical findings demonstrate that woody-grass balance highly affects fire intensity (Higgins et al., 2000). Fire intensity is related to fuel amount, fuel moisture, relative humidity, wind speed, stem height, and under canopy versus open conditions (Govender et al., 2006). The impact of these factors illustrates the importance of fire condition planning for prescribed burn treatments of woody cover. It also illustrates how hyper-local spaces and relatively short time periods can influence factors such as fuel moisture and wind speed, which control how woody cover is affected by the fire events themselves. An opportunity exists to observe these factors over different spatial and temporal scales to test how differences in minute scales can result in regional differences in the relationships between woody vegetation, fire, and climate and how regional contexts affect fine resolution fire and vegetation conditions.

A pyric herbivory conceptual diagram produced by Wilcox et al., 2018 illustrates grass woody dynamics with (a) and without (b) fire (Fig. 1.1).

1.4 Savanna Vegetation Dynamics

Because fire in savannas heavily influences and is in turn heavily influenced by tree-grass balance, the following section provides an overview on grass-tree dynamics in savanna systems to contextualize fire's role alongside other factors influencing vegetation in savanna systems.

The continued existence and functioning of the savanna biome is es-

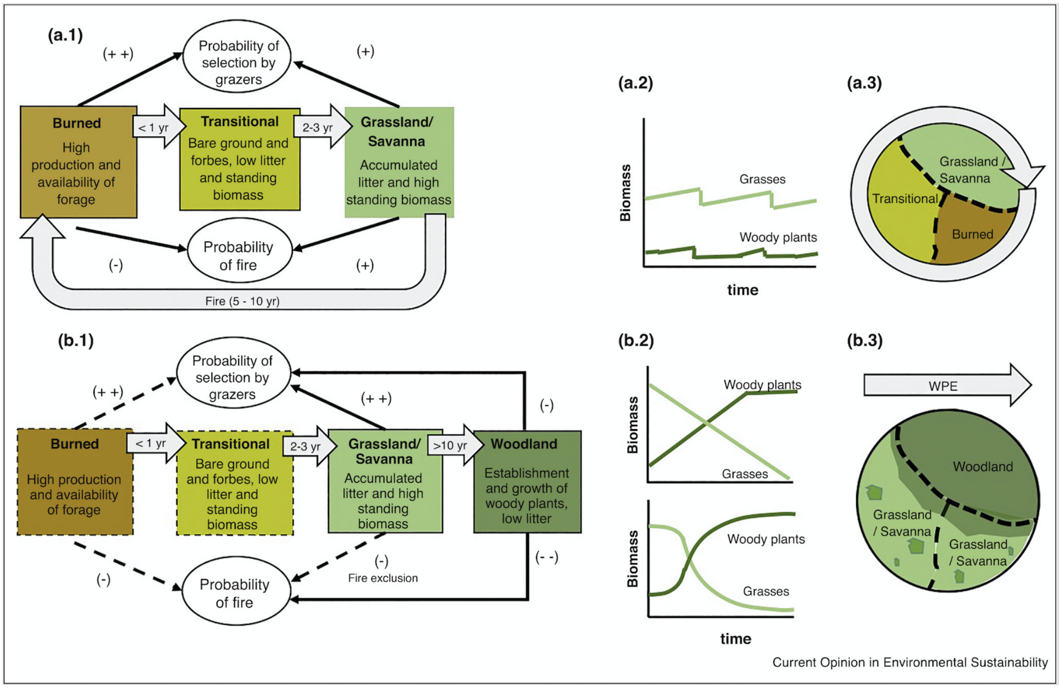

Figure 1.1: Pyric herbivory conceptual diagram produced by Wilcox et al., 2018. a illustrates the feedbacks involved with fire that encourage grass-tree coexistence. b illustrates a lack of fire where grazing leads to a woodland transition.

sential for multiple reasons, both contained within the biome itself and linked to larger biogeochemical cycling, such as carbon storage (Asner et al. 2004). Within the savanna biome are the earth's most expansive areas of rangeland, which serve as critical wildlife habitat and produce animals for human consumption of meat, dairy, and other animal products. These rangelands have a massive spatial footprint and are socio-economically imperative to preserve; they support livelihoods for approximately 550 million people living below the international poverty line (Boone et al., 2018). Notable wildlife habitats in the savanna biome include those within sub-Saharan Africa, which are home to some of the earth's last remaining mega-faunal habitats and contain the highest diversity of ungulate species in the world (Mali et al., 2016). For example, the Cerrado region of South America contains some 160,000 plant, fungi and animal species (Klink et al., 2005). The biodiversity and ecosystem functioning of these areas within the savanna biome both depend on resources and ecosystem services that are ultimately provided by savanna vegetation.

Herbivores that are dependent upon on savannas vegetation fall into one of two categories depending on their type of herbivory: The grasses support wild and domestic grazers, while the more woody species present in tree clumps support wild and domestic browsers (goats). Therefore, the management of savanna systems, both wild and domestic, is concerned with maintaining the continuous grass layer as well as woody vegetation patches, unless browsers are favored. The balance between the two is often changing and is of vital importance to management, but the determinants of grass/tree coexistence are not universally agreed upon (Case et al., 2018; Yu and D'Odorico, 2015; Lehsten et al., 2016). Ongoing research revolves around the characteristics of processes including the role of water, nutrient availability, and tree recruitment strategies along with the interactions among fire, grazing and other disturbances on savanna vegetation. In terms of their climate, savanna systems are distinguished by a strong seasonality of precipitation that affects vegetation persistence and dynamics (D'Onofrio et al., 2015).

The density of woody plant cover plays a large role in determining the functioning in savanna systems. The structural diversity contributed by the presence of woody plants affects energy, water, and nutrient dynamics by creating patches of shade and light, litter on top-soil, and evapotranspiration (Holdo and Mack, 2014). At certain rates of occurrence, woody species can increase system level biodiversity by 1) creating micro-habitats through lower radiance conditions that allow low light species to grow, 2) changing nutrient levels under canopies, and 3) providing resources to fauna species that rely on browsing from woody plants. Therefore, the existence of the woody species within the patchwork mosaic is a key factor in the functioning of savanna systems at multiple levels.

Under the tree canopies themselves, plant productivity is affected in seemingly disparate ways. There is the potential to increase plant productivity through increased soil fertility and structure below tree crowns from plant litter, and decreased water stress for shaded plants (Belsky, 1994; Prevedello et al., 2017). However, a decrease in below canopy productivity that has been often noted is competition between woody species and under canopy vegetation for soil moisture, energy, and nutrients (Ratnam et al., 2011; Lehmann et al., 2014; Dohn et al., 2016). The directional outcome of productivity depends on 1) ecophysiological factors: individual growth form level canopy structure and rooting systems, photosynthetic dynamics (pathway and evergreen versus deciduous), and resource requirements (light, water, nutrients), 2) climatic and morphologic impacts: seasonality and topoedaphic properties, 3) grazing impacts: the extent of selective grazing, browsing, frequency, and intensity, and 4) occurrence, rate, and intensity of disturbance: namely fire (Scholes and Archer, 1997; Smit and Prins, 2015).

A vast literature about savanna vegetation dynamics spans the subdisciplines of vegetation ecology, rangeland management, climate change drivers and impacts, political ecology and remote sensing, as well as others. These strands of research explore the interactions and feedbacks of drivers at multiple scales and over a large variety of geographic regions (Fisher et al., 1994; Scholes and Archer, 1997; Sankaran et al., 2005; Bond, 2008; Reid et al., 2016; Touboul et al., 2018). Furthermore, these drivers and their effects involve many sets of agents acting across spatial and temporal scales. Despite the depth of the literature on the topic, definitive consensus has not been reached on the interactions of local, regional, and global patterns of savanna vegetation and how patterns are influenced by drivers at multiple scales.

1.5 Water Versus Nutrient Limitations in Savannas

The coexistence of trees and grasses in savannas is influenced by limitation of resources. The two major resource limitations that affect savanna vegetation are nutrients and water that is available to plants. In systems with enough water to support unlimited grass and tree species, soil nutrient content along with soil texture are important factors in tree density (Pellegrini, 2016). Water limitations include precipitation amount and seasonality of precipitation (Stevens et al., 2017). Within water limited systems, the rooting depth of tree and grass species affects what is accessible (Schenk and Jackson, 2002). However, examination of rooting depth alone is not sufficient to explain grass/tree balance and savanna functionality – the interactions among processes are key.

Root niche separation theory posits that grass and tree coexistence exists because of differences in rooting depth, which allow trees and grasses to access resources located at different depths in the soil (Kulmatiski and Beard 2013). Some existing research supports this theory (Schenk and Jackson, 2002), but empirical findings are still needed to address questions about rooting depth differences among different species of savanna trees. Some evidence suggests that species have shallow roots, which compete for resources with grasses while others have much deeper roots to access resources located at depth. It has also been posited that even with different rooting depths grasses and trees are ultimately competing for the same water as it passes deeper into the soil (Nippert and Holdo, 2015). The temporal response and use of resources are also thought to differ among trees and grasses, so there is a possibility of temporal use niche as well (Yu et al., 2017). Hydraulic lift, or hydraulic redistribution may explain the coexistence of grasses and trees through redistribution of soil moisture up the water table via deep rooted trees that allow grasses to access deep soil water (Yu and D'Odorico, 2015; Lee et al., 2018).

Southern African savannas are not only present within different land use types, but also across a range of climate conditions. Sankaran et al. (2005) used data from 854 sites that span the African savanna biome to investigate controls of woody plant cover. Of all of these sites, two distinct types of savanna systems emerged – what the authors characterized as "stable" and "unstable." The stability of a savanna system, they argued, was determined by the resource availability along with fire, particularly whether nutrients or water served as the limited factor on a system's vegetation. African savanna systems that received less than 650 mm of mean annual precipitation were considered to be water limited. These systems were classified as stable because they have a capacity for woody plant cover that falls short of a full canopy because the lack of water allows woody plants to outcompete grasses. Therefore, this capacity for woody plant cover is linearly related to mean annual precipitation received. In areas that received more than 650 mm of mean annual precipitation, there was sufficient precipitation for a full woody canopy. These systems with greater than 650 mm of mean annual precipitation were classified as unstable because full woody cover is only reached under conditions of disturbances such as fire and grazing, which are highly heterogeneous in space and time. Therefore, the authors concluded that there are large areas of the African continent in which woody cover in savannas is controlled by factors beyond resource limitation.

1.6 Tree Recruitment and Seed Dynamics

Tree recruitment and seed dynamics affect the dispersal of woody species and the persistence of these patches within the savanna mosaic. Tree recruitment includes ecological aspects such as stem mortality, resprouting, and growth rates; seed dynamics includes seed production, dispersal, seed bank decay, and seedling establishment, all of which interact to affect tree recruitment in savannas (Golos et al., 2016; Wilson and Witkowski, 2003). These interactions ultimately affect the probability of survival of tree seedlings when faced with competition with faster-growing grasses, disturbances such as fire, and resources such as precipitation (Kraaij and Ward, 2006). Even before a seedling exists, the dispersal and storage of seeds are imperative to determining what species of trees grow, where they grow, and when they grow. The seed's longevity and distributions therefore influence the dynamics of tree recruitment and therefore the proportion of woody cover within a particular savanna ecosystem.

Seed production, often referred to as tree fecundity in woody savanna species depends on tree size, species and maturity. Trees must reach a species specific height and maturity to produce seeds (Higgins, 2000). Seed production also varies among tree species in terms of the longevity of the seed's ability to germinate. In the case of local dispersal, longevity is not as crucial to survival as it is in cases of long-distance dispersal. Resulting soil seed banks may vary in density due to dispersal ranges and longevity of the seed. Local dispersal dynamics influence seed bank density because of the clumping nature of trees in savanna systems. Long distance dispersal is dependent on seed distribution via mammals, birds, and insects.

Following dispersal, the establishment of the seedling is highly influenced by herbivory, precipitation and competition with grasses and shrubs (te Beest et al., 2015; Hoffmann, 1996). Seedlings are also vulnerable to mortality during fire. If a seedling matures enough so that competition with grasses and small shrubs is less of a concern, it will also be less vulnerable to fire and herbivory. At this point, the survival rate is high and seedling establishment is relatively successful (Stevens et al., 2018). Existing empirical evidence suggests that many savanna tree species live over 500 years (Veldman et al., 2015). This longevity is in part due to a resilience to drought and the capability to resprout after top kill resulting from fire, both evolutionary advantages that help the tree species survive in savanna ecosystems (Stevens et al., 2018). In particular, the role of fire in killing tree seedlings, but not mature, fire-adapted trees which survive or resprout following fire, is a central component of grass-tree coexistence, which is explored in the following section.

1.7 Utilizing Remote Sensing for Analyses of Savanna Ecology

The ability to sense and record fire in savannas has fundamentally changed the research questions and methods that are used to observe and understand fire dynamics. Remote sensing provides for an unparalleled record of fires occurrence in the present as well as a window into the past. Remotely sensed datasets allow researchers to investigate questions of fire return interval and fire history that would be difficult to capture using field-based methods (Giglio et al., 2006). These studies have facilitated significant steps towards understanding spatial and temporal fire dynamics, but have also introduced novel extents and resolutions in which to study the interactions of fire and savannas.

Remote sensing encompasses more than studies of satellite imagery. Wigley, Bond, and Hoffman (2010) used aerial photography (1m resolution) from 1937, 1960, and 2004 to quantify woody cover change in 4 land use types with similar climate, topography and soils in KwaZulu-Natal, South Africa. Conservation, communal, and commercial land uses had significant gains in woody cover from 1937 to 2004. Commercial land uses had the most significant increase in woody cover from 3 percent to 50 percent, woody cover in conservation land uses increased from 14 percent to 58 percent, and woody cover in communal rangelands increased from 6-25 percent. These results make a compelling case that global and local drivers of woody encroachment are both important given that woody encroachment was present and significant across land uses, but also exhibited markedly different magnitudes across land use types in a relatively small region. Of particular note, conservation areas had a higher growth of woody plant cover than communal grazing lands. This growth is likely due to possible fire exclusion/suppression in conservation areas, as well as decreasing predator populations leading to larger grazing populations. The magnitude of woody encroachment in commercial grazing land compared to communal grazing suggests that intensity of livestock grazing in the region is a determinant of woody cover. This study is a prime example of the use of remote sensing to investigate particular regional dynamics.

The availability of multiple data products and multiple images of each data product has resulted in a plethora of options in terms of observation, analysis, and geographic scale that can potentially make the analyses difficult to compare, even when they contribute to understandings of individual systems. The effects of these varying scales in the understanding of fire are not well understood. Effective fire management demands that scientists understand the impacts of scaling on not only their specific research results, but more broadly in terms of initiating management strategies based on this research. For example, these questions may be particularly relevant for land managers who may be interested in the dynamics of an area of land that is less than 500 meters by 500 meters, which would be captured in a single pixel using the MODIS satellite products (Giglio et al., 2006). Opportunities exist to explore the linkages and influences of fire and vegetation across extents and resolutions in savanna systems to form a more holistic understanding in the role of fire in savannas.

1.8 Consensus and Remaining Questions

Savanna fire and vegetation patterns are affected by a combination of processes, feedbacks, and drivers at diverse spatial extents and resolutions, but the linkages and interactions of fire and vegetation patterns at separate extents and resolutions are not well established. Grass-tree balance in savanna systems is a main focus of management, and is affected by water and nutrient availability, fire and grazing, and tree recruitment. This thesis explores the influences of climate, biological and human systems on savannas fire and vegetation patterns at different spatial extents and resolutions in Botswana, and focuses on identifying how large factors influence local patterns and how local factors influence large patterns.

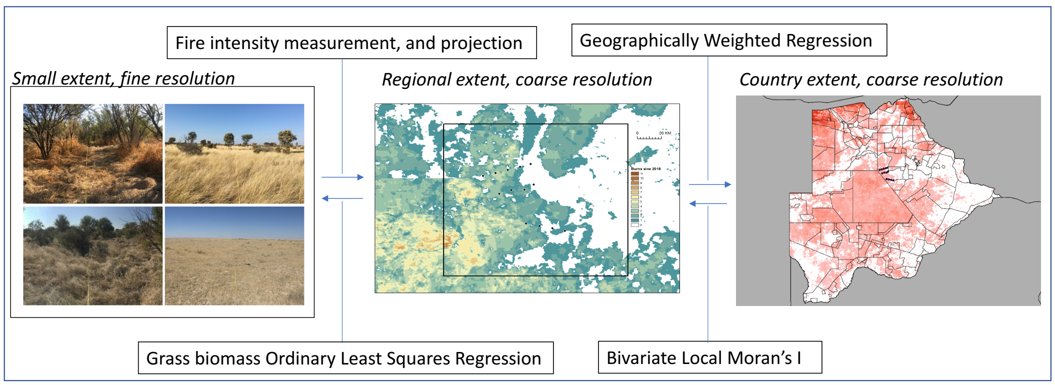

Figure 1.2: Analyses performed to observe interactions of savanna fire at different extents and resolutions

A variety of methods were used to explore the interactions of fire at different extents and resolutions. The effects of neighboring fire regimes and fuel conditions through time were tested using Bivariate Local Moran's I–a novel method for observing spatiotemporal fire dynamics. To observe how spatial variations of factors among 500m pixels affect larger patterns of fire occurrence Geographically Weighted Regression was used. The effects of fire, competition, herbivory, and climate on grass biomass were tested using *In situ* vegetation measurements to produce an OLS regression model. Fire effects on vegetation were observed following a fire in the study area by measuring vegetation mortality and fire intensity.

Chapter 2

Study Area

Analyses were performed at three varying scales. Country level analyses were performed for fire history and seasonality. Regional scale analyses were performed for the Botswana Kalahari excluding the southern 3rd of the country (below -23.312 dd). Finer scale analyses and field work occurred in a shared human-wildlife savanna system in East-Central Botswana located directly outside of the eastern fence of the Central Kalahari Game Reserve (Figure 2.1).

2.1 Kalahari Study Area

The Kalahari region in Southern Africa has multiple definitions, but in the context of this thesis it is defined as a plateau occurring at 1000 m to 1200 m above sea level, between the latitudes of 121-281S and longitudes 151-271E, and containing relatively homogenous well-draining sandy soil that extends across the region. The sandy soils of the region form one of the largest extents of surface sand (sand sea) on earth. Relatively constant soil and topography in the region make it a scientifically vital area for studying the interactions between rainfall, nutrient availability, fire, herbivory, and vegetation at large spatial scales because these affects can be observed independently of soil influences. The Kalahari Transect– an International Geosphere–Biosphere Programme-designated mega Transect– is a prominent initiative with a goal to generate understanding along the north south rainfall gradient present in the Kalahari (Scholes and Parsons, 1997).

Sand grain size, bedrock depth, and mineral composition affect vegetation distribution in the Kalahari (Moore and Attwell, 1999). Grain size and mineral composition increase on the edges of the Kalahari basin, where there is shallower bedrock. The sand comprising the Kalahari basin is nutrient poor and is comprised mainly from particles weathered by Aeolian processes. Parent material and bedrock are classified in The Karoo supergorup – Calcrete, sandstone, schist, and shale. Outcrops of calcrete, sandstone and schist occur intermittently throughout the region. Relationships among surface nutrients, soil crusts, and vegetation exist in the Kalahari (Dougill and Thomas, 2004). The increase of biological surface crust under areas with high woody density increases local soil nutrients potentially leading to a positive feedback loop causing woody species density to increase (Thomas and Shaw 1991).

In this context, the Botswana Kalahari refers to the area of Botswana north of -23.312 latitude. There is a gradient of increasing annual rainfall from the south to the north, excluding the Eastern precipitation belt. Annual mean monthly rainfall amounts range from 26 mm to 42.94mm (Abatzoglou et al., 2018). The region's weather patterns are influenced by air from the Atlantic and Indian Oceans. Virtually all the rainfall in the area occurs during the austral summer (October-March). Precipitation in the Austral summer is highly spatially and temporally variable, the coefficient of variation follows a gradient from relatively low in the north (37percent for Maun) to relatively high in the south (44 percent for Tsabong) (Shugart et al., 2004).

The Kalahari savanna system exists in a middle zone regarding resource limitation. The semi-arid classification of under 500 - 600mm annual rainfall applies to some areas of the Kalahari (southern and eastern-central), but others experience the amount of rainfall to be considered non-water limited (650mm mean annual precipitation) (Scholes et al., 2002; Sankaran, 2005). Up to 400mm MAP favors Mimosaceae *Acacia* species, between 400 and 600mm MAP favors Combretaceae and Colophospermum *mopane* species, and above 600mm favors *Caesalpinaceae* species other than Mopane (Scholes et al., 2002). Further complicating this middle zone is highly spatiotemporally dynamic inter-annual precipitation and heterogeneous rainfall across the central Kalahari. The fieldwork study area is also a middle zone regarding resource limitation and is characterized by highly spatially and inter-annually heterogeneous precipitation. The study area sites received a range of 285-703 mm per year since 2012. In the Kalahari region, high interannual rainfall variability leads to a competitive advantage of trees that have deeper roots than grasses (Yu et al., 2016), and grass cover is highly correlated with variability in wet season rainfall (Scanlon et al., 2005).

The primary factors affecting savanna vegetation structure and composition in the Botswana Kalahari are precipitation patterns, nutrient availability, fire and herbivory (Higgins et al., 2007, Levick et al., 2012). A general pattern of increasing woody plant biomass is observable along the south to north gradient with mixed broad-leafed and microphyllous species in the north and microphyllous dominance in the south (Shugart et al., 2004), but there is a high amount of heterogeneity in vegetation structure – 6 distinct vegetation morphology types were mapped within the Central Kalahri Game Reserve: woodland, dense shrubland, open shrubland, very open shrubland, open herbaceous, and bare/pan (Mishra et al., 2014). Plant species diversity is relatively low, and community assemblages are controlled by species dominance, making the classification between vegetation types and communities challenging. Furthermore, identifying potential factors/drivers (i.e. grazing, fire) of vegetation composition and structure is a major challenge. Pans and dry river valleys with clay-rich soils (fossil drainage from Pleistocene) are present in the Kalahari. The drainage lines typically feature an herbaceous layer and varying woody plant density. Pan characteristics often create buffer areas of vegetation that are influenced by flooding and soil environments. Saline pans, e.g. Makgadigadi Pan, are either bare or are covered by halophytic grasses and shrubs while non-saline pans are typified by Cyperaceae vegetation (sedge) and grasslands, with some cases of clumped woody cover, e.g. Nxai Pan. There are often small areas (typically 1 or 2 meters) of densely wooded vegetation associated with perennial rivers and seasonal rivers. Wetlands – notably the Okavango Delta – support reeds, Papyrus, and floating macrophyte communities (Thomas et al., 1991).

2.2 Land Use

A large portion of the Botswana Kalahari study area is dedicated to various forms of wildlife/natural resource conservation, preservation, and eco-tourism. The Central Kalahari Game Reserve covers a large expanse of the Central and Southern portions of the study area (Figure 2.2). Large areas of pastoral and arable land are in the Central and South Eastern regions of the study area, as well as the Northwestern corner. The largest stocking rates of cattle, goats, and sheep are present in the Central District. Overall human population densities across the study area are quite low. The largest human population centers in the study area are in the Eastern portion of the Central District and the North-East District (Francistown, Mahalapye, Slebi-Phikwe, and Serowe).

2.3 Field Work Study Area

The fieldwork study area is bounded by the Northeast corner of the CKGR in the north, and the fence running along the road directly south of the transects to the south. The Western Boundary of the study area is the Eastern fence of the CKGR and the Eastern boundary is the unnamed (Google Maps, 2018) tar road running next to town of Rakops. This area was chosen because it is an important area socioeconomically and ecologically where there is a high density of domestic and wild grazing, browsing, and predation. There is very little human infrastructure within the study area besides three unpaved roads, boreholes, and fences on the boundaries of the study area. Both the human and natural grazing systems rely on functioning savanna vegetation conditions characterized by large areas of grass interspersed with patches of trees (Thomas and Twyman, 2004). Fire is an essential aspect of these functioning conditions and is therefore highly impactful on both human and wildlife systems, but little is understood about fire in the system.

The regional study area reflects Kalahari physical conditions (sandy homogenous soil and level elevation). Additionally, given the size and location of the study area, relatively homogenous patterns of precipitation, seasonality, and coefficients of precipitation variation are observed across the study area. The vegetation conditions in the study area do not reflect the homogeneity observed in the physical and climatic settings–species, structure, and biomass (including grass versus woody) conditions are highly heterogeonous, making it likely that the grazing and fire dynamics of the area play a key role in the observed diverse vegetation conditions observed within the study area.

The vegetation plots occur within the Tlhabala formation of the Lebung Group characterized by Aeolian sandstone. The Ngwako and Ngami formations, which belong to the Ghanzi Group, occur to the West/Northwest of the plot locations. The Stormberg Lava group is located to the south and directly west of the southernmost plots.

2.4 Fire Background

A fire occurrence map and fire seasonality charts from 2000-2018 are provided in this section for background. Methods for these products are detailed in Chapter 3 (Fig. 2.7-2.9)

In the Botswana Kalahari, large fire events were contained within the range of day of year 200 and 280 in the period of 2000 to 2009. From 2010 to 2017 large fire events happened within a range from day of year 200 to 325. In the fieldwork study area there was one particularly large fire recorded in 2006 that burned a significantly larger amount of area than any other fires in both time periods. The large fire was an early dry season fire occurring around day 235. Excluding that fire event, fires from 2000 to 2009 were constrained from day of year 245 to 330. In the time-period of 2010 to 2017 fire events were relatively limited to day of year 250 to 300 (Figure 2.8).

Fire characteristics and effects on savanna vegetation systems are highly dependent on timing and previous burn history. The amount and moisture content of fuel determines how hot a fire burns and the amount of tree mortality (Higgins et al., 2000). Recent literature has focused on the importance of seasonality on fuel conditions (Govender Navashni et al., 2006; Laris et al., 2017; Platt et al., 2015). Late dry season fires in savannas tend to be hotter and account for more tree mortality because of dry built up fuel. This scenario is generally desirable for managers in woody encroachment prone areas.

The observed changes of seasonality patterns indicate that in Botswana there has been an increase in late season burning and a decrease in early season burning. This implies that there were generally hotter fires burning from 2010 through 2016, due to drier and larger amounts of fuel. According to the southern Africa savanna ecology literature this means that there are likely higher rates of tree mortality during these late season fire events.

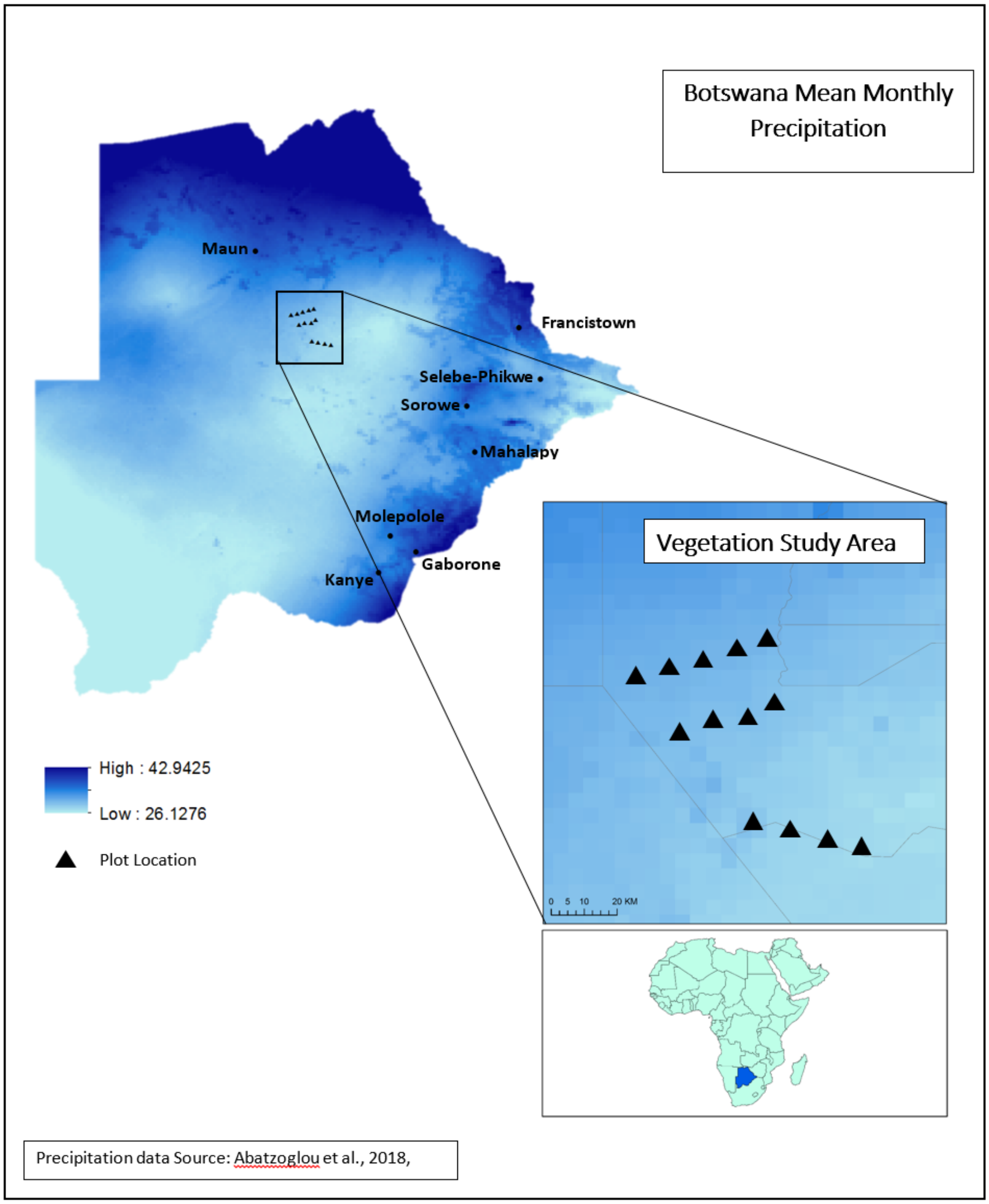

Figure 2.1: Mean monthly precipitation in millimeters for Botswana and the vegetation study area

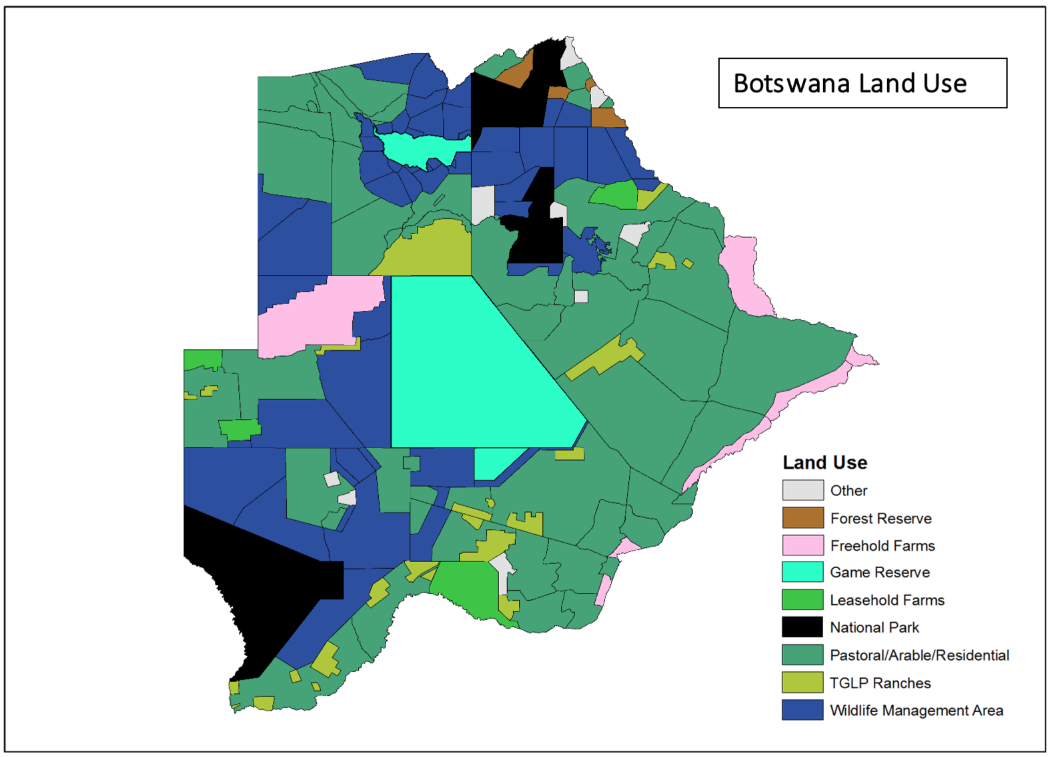

Figure 2.2: Land Use, Source: Digital Atlas of Botswana

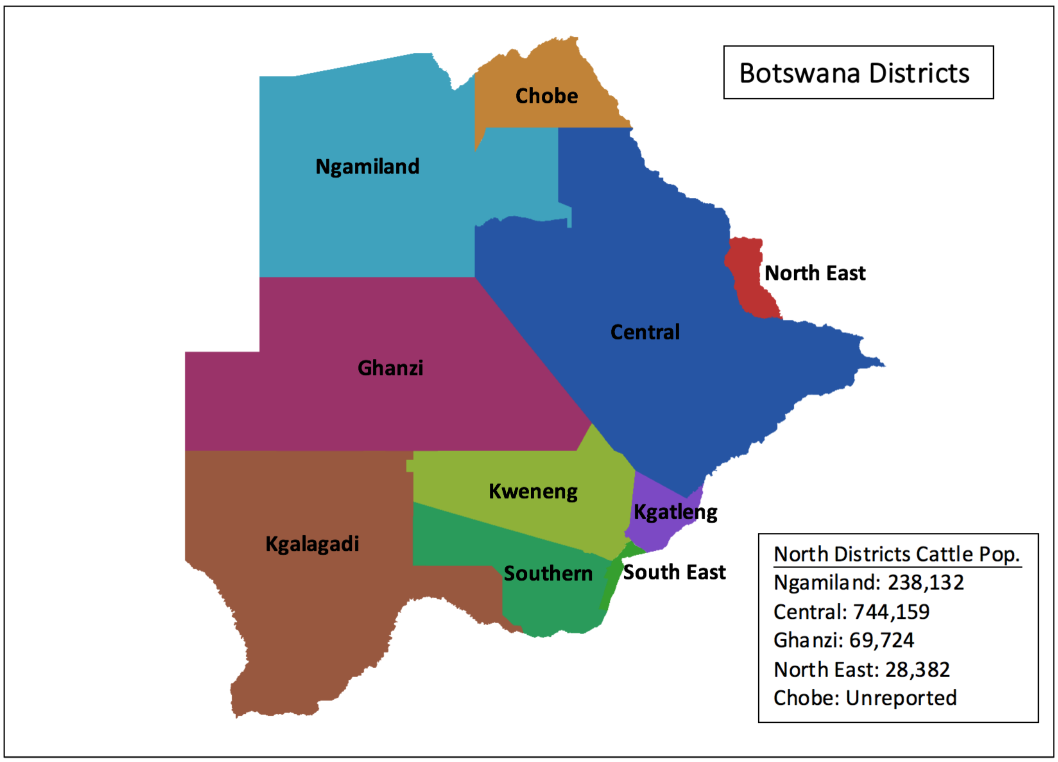

Figure 2.3: Cattle Population Source: The 2015 Botswana Agricultural Census, Statistics Botswana

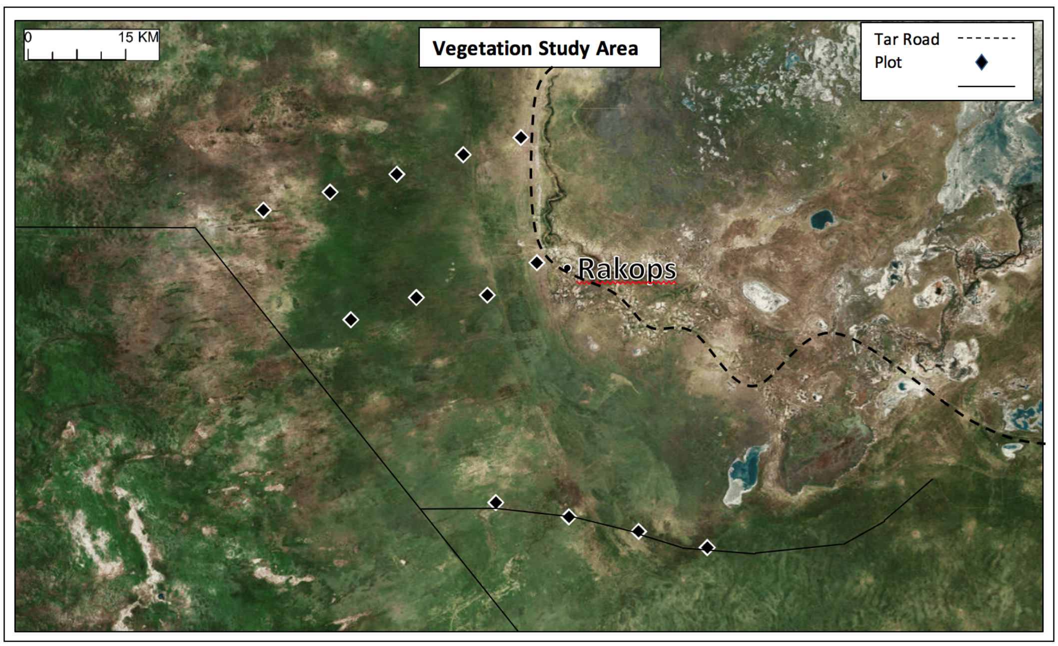

Figure 2.4: Imagery source: Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, Swiss topo, and the GIS User Community

Figure 2.5: Photographs taken at 4 of the 13 transect locations. Diverse vegetation conditions are observed at the 4 sites.

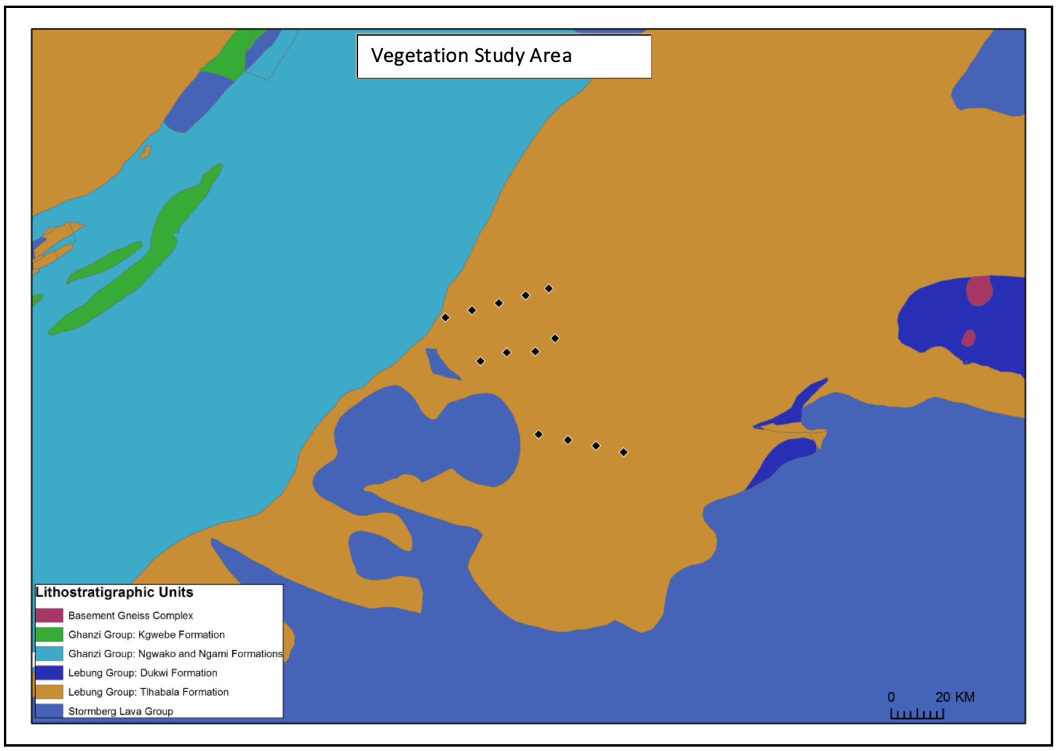

Figure 2.6: Source: Digital Atlas of Botswana

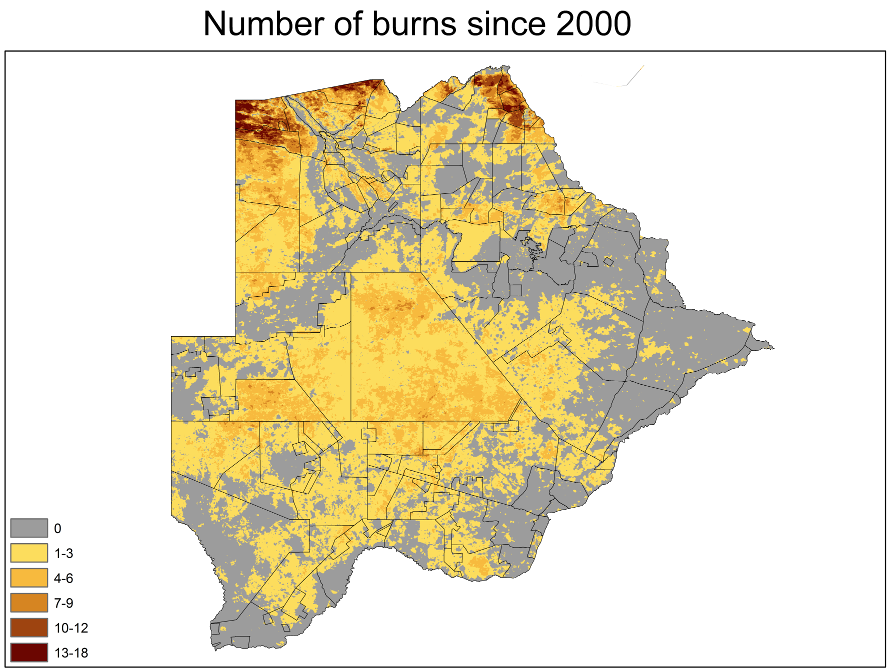

Figure 2.7: Country level Botswana fire history map since 2000 produce using data from the MCD64A1 Version 6 Burned Area data product

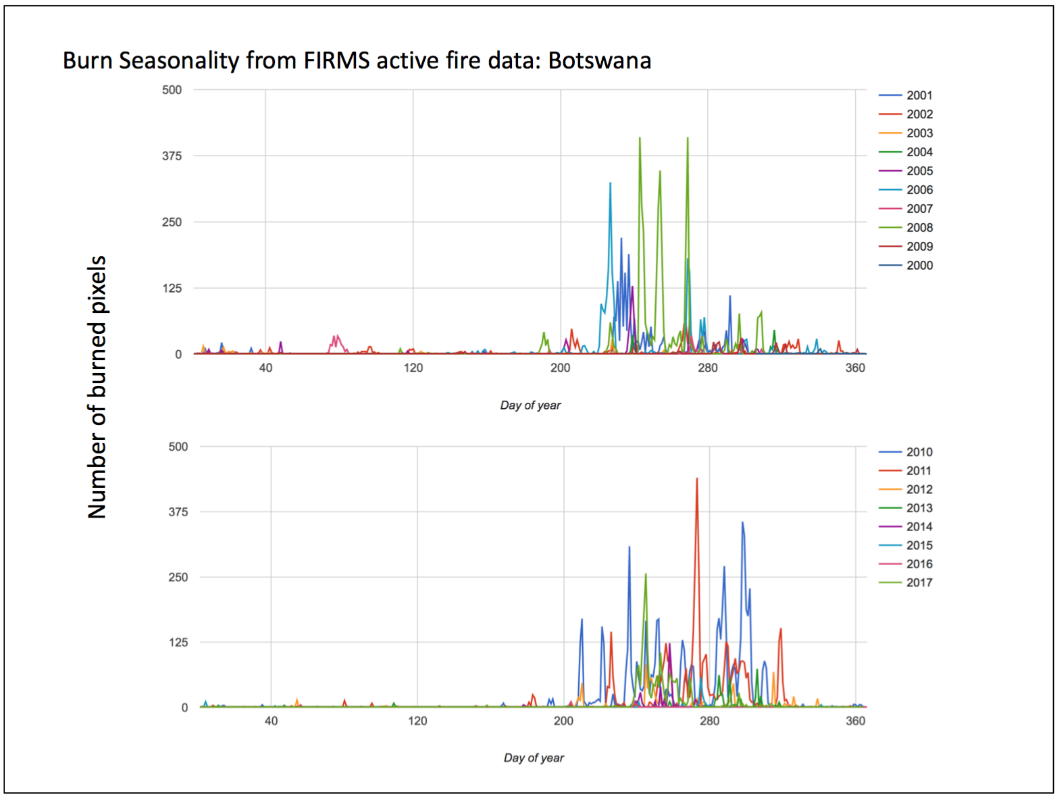

Figure 2.8: Number of pixels burned are color coded by year and charted over day of year for Botswana.

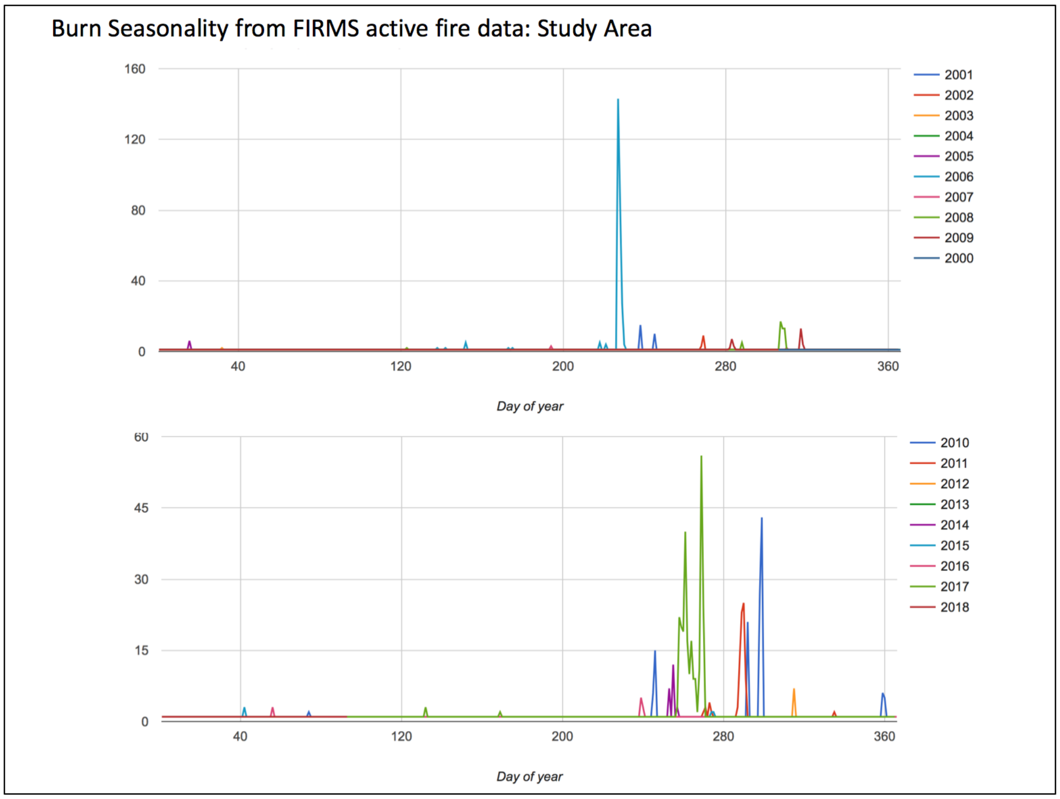

Figure 2.9: Number of pixels burned are color coded by year and charted over day of year for the vegetation study area.

Chapter 3

Patterns and drivers of regional scale fire occurrence in a savanna system

3.1 Introduction

To understand the driving factors of savanna structure and function, the spatial and temporal patterns of those driving factors must be observed (Aleman and Staver, 2018; Levick et al., 2009). In the past, fire has been among the most difficult variable to monitor spatially over large areas and through time, but the introduction of multispectral satellites with global coverage has allowed for fire to be observed over space and time (Giglio, 2016). Spatial and temporal fire patterns allow for observations about where, when, and how often fire events have happened. The relatively short fire return intervals in savanna systems mean that 20-30 years of satellite data can show very valuable information that can start to show how fire regime affects vegetation. This allows research into how fire return rate affects ecosystem structure in specific regions and the interaction of fire with other variables.

Grazing pressure, grass biomass, fuel moisture, soil moisture, precipitation, and ignition sources affect if and how an area will burn (Roques et al., 2001). Satellite fire data allow analyses to measure the impact and magnitude of various drivers that can ultimately lead to regional and local specific understandings of fire's role in a savanna region, as well as what factors affect presence and rate of fire.

The spatiotemporal patterns of fire affect savanna structure and function profoundly in anthropogenic and ecological savanna systems. This paper presents a regional spatiotemporal analysis of fire patterns from 2000 to 2016 that uses remotely sensed data, bivariate local Moran's I (Bivariate LISA), global regression, and geographically weighted regression to explore the spatial autocorrelation of fire return over time, and the long-term drivers of fire occurrence over space. The goals of the paper are to inform the following questions: How do large patterns of fuel dynamics affect neighboring areas across time and space? Does variability of variables over small spaces influence larger patterns of fire occurrence?

3.2 Fire Data

Fire seasonality patterns in the Botswana Kalahari and the fieldwork study area were observed using FIRMS Active burn data that provided a pixel count of fires each day of the year from 2000 to 2018. These data were acquired and plotted by day of year for each year since 2000 using Google Earth Engine. The period of 2000- to 2009 was compared to the period of 2010-2018 to observe changes in seasonal burning patterns. Maps from these analyses

MODIS Terra and Aqua combined MCD64A1 Version 6 Burned Area

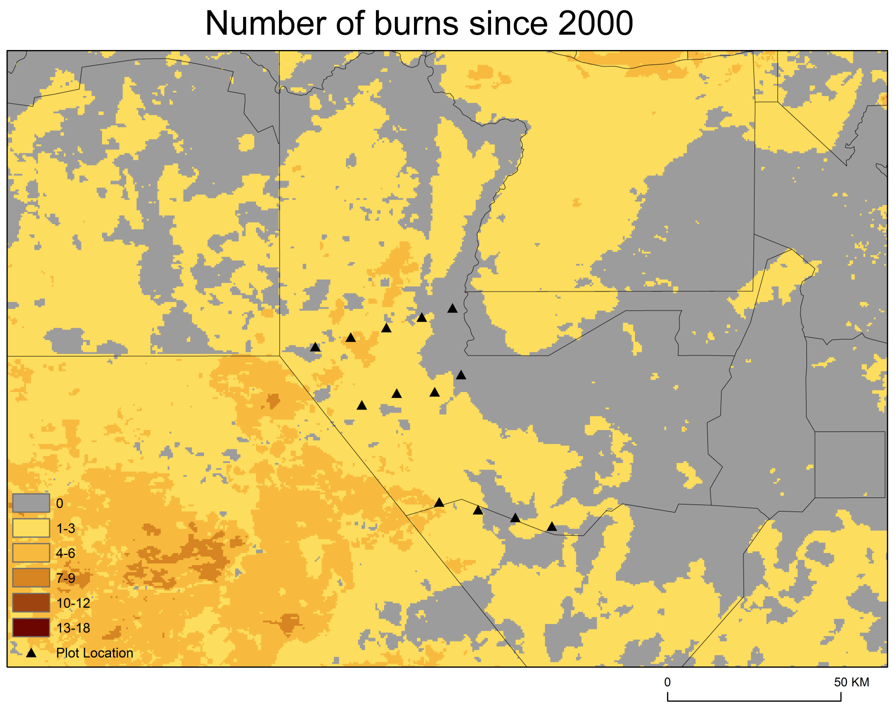

Figure 3.1: Number of fires per pixel since 2000

data product (Giglio et al., 2015) was compiled by the author using Google Earth Engine (Gorelick et al., 2017) to produce the number of years of fire occurrence per pixel (500 m) since the year 2000. In each year burn dates were processed and filtered using QA bands for non-water pixel, vegetation fire, and sufficient timing period for burn detection. The burn dates were transformed to binary to distinguish burned from unburned pixels. The binary burned/non-burn pixels were then summed from each year to obtain the number of years burned from 2000-2018. Because of the binary transformation, the final data does not count multiple burns within a single year, instead the number of years in which a pixel burned. Years with multiple burns are unlikely in most regions of Botswana, including the vegetation study area because there is not sufficient precipitation for sufficient fuel accumulation (Yu et al., 2016).

3.3 Regression Data

Multiple datasets were used to test the effects of multiple variables on fire occurrence using an OLS regression and a GWR regression.

Table 3.1: Variables used in the geographically weighted regression

GWR Variables	Observation #	Mean	Std. deviation	Min	Max
Climate					
Mean Monthly Precipitation (mm)	4,347	30.50147	2.293716	26.2791	36.10379
Seasonality of precipitation (coefficient of variation)	4,347	97.64527	2.36825	92	103
Annual Max Temperature (*10)	4,347	319.0475	2.00669	310.6592	325.1571
Temperature Variation	4,347	3940.066	84.2573	3744	4142
Palmer Drought Severity Index	4,347	-3.371275	2.663906	-9.722301	7.41094
Soil Moisture	4,347	18.22593	11.33294	4.279102	47.9425
Population and grazing					
Number of boreholes within 5 km	4,347	938.7099	3209.055	0	15765
population	4,347	0.0118267	0.0688917	0	1.440964
Fire					
Burns since 2000 (MODIS 64)	4,347	1.328042	1.430087	0	7
Vegetation					
EVI (*100)	4,347	2088.741	299.9817	659.485	2710.874
NDVI	4,347	0.2563011	0.0537328	-0.0656285	0.6260276
Herbaceous cover	4,347	57.86427	15.52788	0	81

Google Earth Engine was used to acquire climate datasets for the geographically weighted regression. Seasonality of precipitation and temperature are long-term historic climate data available from the WorldClim V1 Bioclim dataset at 30 arc seconds (Hijmans et al. 2005). Mean monthly precipitation, maximum annual temperature and soil moisture were acquired from TerraClimate monthly climate and climatic water balance for global terrestrial surfaces dataset that covers the time-period 2000 to present at 25 arc seconds (Abatzoglou et al., 2018). EVI, NDVI, and Herbaceous cover measurements were acquired from the MODIS MOD13A1 V6 product from the period 2000 to present at 250 meters (Didan, 2015). The borehole data were acquired from the Digital Atlas of Botswana (DSM, 2003). Boreholes are dug in areas of dense cattle grazing to provide water so boreholes are used as a proxy for grazing (Moleele, 2002). The population dataset was acquired from The Gridded Population of World Version 4 model (CIESIN, 2016). A fishnet was produced to convert the borehole point dataset to a raster dataset.

All the data were projected to UTM and resampled at 500m spatial resolution. Variable selection was focused on minimizing multicollinearity of the independent variables. Precipitation and soil moisture, NDVI and EVI, and seasonality of precipitation and temperature were highly multi-collinear according to the variance inflation factor test (VIF) where values greater than 10 are a sign of multicollinearity. EVI, soil moisture, and seasonality of precipitation were used in the model because they had stronger correlation with fire occurrence compared with the respective collinear variables. The residuals of the final model are slightly non-normal, but it is a very large dataset – 4,347 observations and the model is not a predictive model.

3.4 Spatiotemporal Methods

To observe fire return intervals and the effect of burning on surrounding areas Bivariate Local Moran's I (Bivariate LISA) analyses were performed using MODIS Burned Area Monthly data. Fire counts were binned into 3-year time periods from 2000-2002, 2003-2005, 2006-2008, 2009-2011, and 2012-2014. Local Moran's I relates an individual observation to its neighbors and assigns each observation a category and a degree of spatial autocorrelation (Anselin, 1995). The local Moran's I measures the degree of similarity in a given variable between observation i and observations j in the neighborhood of i defined by an assigned weight matrix. Bivariate LISA is an extension of local Moran's I where the spatial autocorrelation of two different variables is measured between observation i and observations j. Bivariate LISA has been used in a wide variety of areas to assess spatial-temporality, but is an underutilized method in ecological applications (Stucki et al., 2017). In the ecological realm, Bivariate LISA has been applied to risk assessments of insect outbreak (Bone et al., 2013), tree line dynamics (Carrer et al., 2013), and Wildland fire risk and social vulnerability (Gaither et al., 2011). Spatiotemporal dynamics of vegetation can be observed with Bivariate LISA (Goḿez et al., 2011), but it has not been utilized to observe the spatiotemporal dynamics of fire regimes.

In this case, Bivariate LISA allows the spatial autocorrelation between fire occurrence from two different time periods to be compared, providing a measurement of burnt area and non-burnt from one time period to the next to show how fire activity of a given location affected fire activity in the surrounding area in a later time period. The Geoda software package (Anselin et al., 2006) was used to calculate Bivariate LISA. For the datasets to be compatible with the Geoda software the stacked raster product was converted to a table. A queen neighborhood function was used to calculate Bivariate LISA with a neighborhood order of 2 (including lower orders) to pick up on larger burning patterns and to avoid only picking up hyperlocal effects. An initial 3 year burn count was compared to the following 3 year burn count. Categories of spatial autocorrelation were assigned as: statistically significant areas of high burning in the initial period surrounded by areas of high burning in the lagged period (H-H), areas of low burning in the initial period surrounded by areas of low burning in the lagged period (L-L), areas of high burning in the initial period surrounded by areas of low burning in the lagged period (H-L), and areas of low burning in the initial period surrounded by areas of high burning in the lagged period (L-H).

3.5 Regression Methods

The spatial dynamics of long term variables influencing fire occurrence in the study area are not understood. Local regression models offer an exploratory method that shows where explanatory variables are significant and the magnitude and sign of those variables at each local observation. Geographically weighted regression (GWR) is a tool for exploring the spatial variability of local variable relationships (Brunsdon et al., 1996; Fotheringham et al. 2003). GWR methodology has been widely used for analyses with remotely sensed data because coefficient significance, signs, and magnitudes can be mapped spatially with continuous raster data (Hu et al., 2018; You et al., 2015; Song et al., 2014). Ecological applications of remotely sensed data and GWR have included spatial explorations of the NDVI-rainfall relationship (Georganos et al., 2017), environmental parameters of viruses (Kala et al., 2017), and fire (Oliveira et al., 2014). The spatial dynamics of fire at the extent of Sub Saharan Africa were explored by Sá et al., (2011). At the continent scale, the importance of local spatial analysis of model performance is apparent because fire occurrence in most of Southern Africa is not explained by the model because fire occurrence in the southern region is drowned out by much higher rates in the tropics. This highlights the need to develop a region specific explanatory fire occurrence model that can explain spatial variation for a regionally specific extent.

Initially an Ordinary Least Squares (OLS) regression was performed on the variables as an initial global model with which to compare subsequent models. A Poisson global linear model was then produced because fire count data is a Poisson distribution made up of integers. The variables were tested for multicollinearity using a variance inflation factor test – EVI: 3.91; Herbaceous: 3.47; PDSI: 1.32; soil moisture 5.28, borehole 1.03; seasonality of precipitation: 4.07–indicating the absence of high multicollinearity. The variance was slightly higher than the mean, which breaks the PGLM assumption that variance equals mean, but the model fit was examined using a Deviance goodness-of-fit test (4074.805, Prob chi 2(4284) = 0.9998) and a Pearson goodness-of-fit test

(3525.28, Prob chi2 (4284) = 1.0000). The highly insignificant chi squared statistics indicate good model fit. Although the variance was slightly higher than the mean a Poisson Global Linear model was used because of model fit. The marginal effects were compared between the OLS and Poisson GLM. The variables in Poisson GLM had higher partial effects than each of the variables in the OLS model. GWR 4.0 software (Nakaya et al., 2009) was used to produce a geographically weighted regression model for the study area using the variables selected. A Geographically Weighted Poisson Regression was used to explore the significance, magnitudes, and signs of the explanatory variables spatially within the study area (Brunsdon et al., 1996; Nakaya et al., 2005). A GWR uses a kernel function for geographical weighting to determine local coefficients. Geographic weighting was attained using an adaptive Bi-square geographic kernel and a golden section search for optimal bandwidth size determined by AICc.

3.6 Spatiotemporal Results

The global Bivariate LISA values for each of the temporal comparisons indicate that regions are influenced by neighbors in multidirectional ways depending on fire presence and the response of vegetation to fire presence. The global statistic for the first comparison was negative. Every other comparison was positive and increased with each successive time comparison. The local values from the Bivariate LISA offered more detailed findings. The proportion of Low-Low cells, representing little burning in the initial period surrounded by little burning in the following period, stayed consistently high throughout all 4 temporal comparisons. The occurrence of High-High cells, representing high burning in the initial period surrounded by high burning in the following period, was low throughout, but increased from very rare in the in the 1st and 2nd period and 2nd and 3rd period (886 and 738) to 24778 and 16173 in the last 2 comparisons. High-Low pixels, representing high burning in the initial period surrounded by low burning in the following period, were behind L-L as the highest occurring association type in the first and fourth comparison. Low- High pixels, low burning in the initial period surrounded by high burning in the following period, were behind L-L as the highest occurring association type in the second and third comparisons (Table 3.2, Figures 3.2 and 3.3).

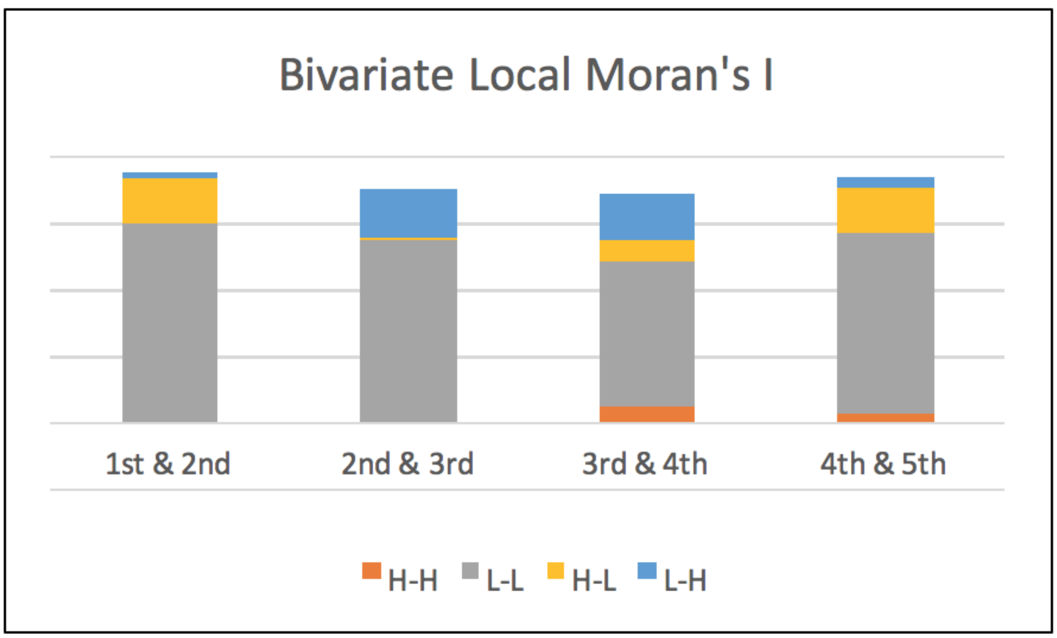

Figure 3.2: Bar graphs showing the ratios of of bivariate LISA classifications

Table 3.2: Pixel tally for each classification from the bivariate LISA. Global Moran's I is also shown for each time period comparison.

	1st & 2nd	2nd & 3rd	3rd & 4th	4th & 5th
Global Moran's I	-0.0034	0.019*	0.1399*	0.1657*
H-H	886	738	24778	16173
L-L	298910	275901	217828	270157
H-L	69285	1347	32922	67559
L-H	6448	74433	68592	14880

3.7 Regression Results

Adjusted R squared from the OLS (0.226) and psuedo R squared (0.108) from the Poisson model indicated that the explained fire occurrence was low in the study area. Both global models indicated significance for each variable used. All the variables included in the models were statistically significant, but the relatively low R squared values indicated that fire presence at this scale and region was not adequately explained by the global models.

The AICc is a measure of model performance, which is helpful when comparing models with the same dependent variables. The AICc from the GWR model (2998.314) is lower than the AICc of the global model (6076.938).

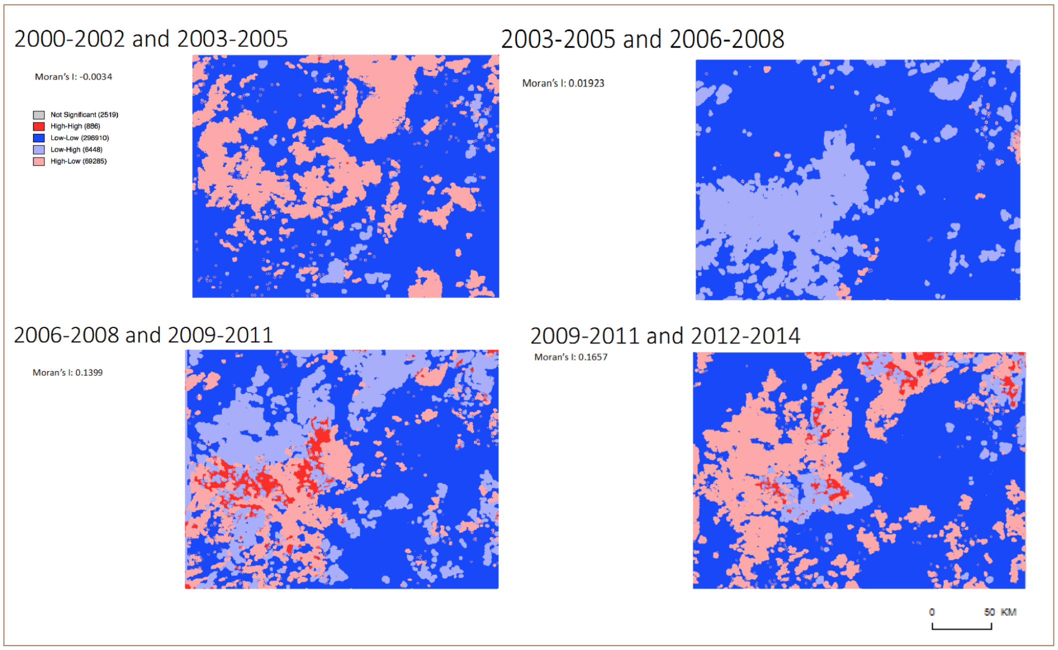

Figure 3.3: Maps produced from the bivariate LISA output

The most similar metric to an R Squared from a Poisson GWR is the percent deviance explained. A comparison between the global deviance explained and local deviance explained is helpful to get a sense of spatial heterogeneity, but caution must be taken because this metric will always improve with the local model because of the nature of the calculations. As expected the percent of deviance explained improved with the local model from 0.205 to 0.623. The ranges, means, and quartiles of the local coefficients are listed below in Table 3. Soil moisture had the highest range and borehole had the lowest range, but the ranges reflect coefficient magnitude which is affected by the measurements which are not normalized. Herbaceous cover percentage had the most positive mean and median, while precipitation seasonality had the

Table 3.3: Results from the OLS and poisson model

Independent variable: Fire occurrence	OLS adj R^2: 0.2264	Poisson % Deviance explained: 0.205			
	OLS Coef.	**Poisson Coef.**	**P>t**	**P>z**	**vif**
Seasonality of precipitation	-0.181058	-0.1211812	0.00	0	4.07
Soil moisture	0.0399617	0.0322756	0.00	0	5.28
PDSI	0.1367893	0.0644431	0.00	0	1.32
Number of Boreholes within 5 km	-0.0000401	-0.0000339	0.00	0	1.03
Herbaceous Cover	0.0413823	0.0420558	0.00	0	3.47
EVI	-0.0015854	-0.0013476	0.00	0	3.91
Constant	19.69481	12.01316	0.00	0	

Table 3.4: Tabular Results From the geographically weighted regression

Variable	Min	Max	Median
Intercept	17.308837	39.819624	10.844377
Seasonality	-0.49283	0.148646	-0.075759
Soil Moisture	-0.175015	0.608923	0.03979
PDSI	-0.249402	0.426039	0.02743
Borehole	-0.001293	0.000058	-0.000033
Herbaceous	-0.017221	0.070891	0.012914
EVI	-0.004961	0.003478	-0.001706

most negative mean and median. Seasonality of precipitation was the only variable with only negative significant local coefficients. No variables had only positive coefficients.

3.8 Spatiotemporal Discussion

A key factor in fuel conditions and vegetation structure and function is how often areas have burned in the past. Establishing temporal conditions of fire in a region is key to understanding overall ecosystem function. There is a vast amount of research regarding southern Africa fire regimes, and the respective effects of different burn intervals, but comparatively there is a lack of research on how regime and return intervals affect surrounding areas. Specifically, how does burning in a given area affect burning in neighboring areas over time?

Between the two spatiotemporal analyses it can be observed that fire occurrence and return is dynamic spatially and temporally in the study area. The spatial autocorrelation of fire occurrence in lagged time periods changed throughout the 14 year period Since it is difficult to construct a reliable fire history before 2000 at these scales, it is presently unclear whether these changes are linear, cyclical, or novel patterns, but it provides an important starting point to compare to future patterns of fire dynamics in the area. It also provides an opportunity to compare to larger patterns across the larger region of southern Africa. An important next step will be to determine whether these patterns are driven primarily by climate, anthropogenic, or other factors.

Fuel connectivity determines where and if a fire will spread (e.g. fire breaks) (Kahiu, 2018). Bivariate LISA is a novel method to explore fuel connectivity by measuring the spatial autocorrelation of fire in two separate time periods providing information on the effects of fire in neighboring via fuel dynamics. The findings from the analysis support the hypothesis that fire occurrence is influenced spatially by past occurrence, and that reoccurrence follows a spatial and temporal pattern. These dynamics were classified and measured.

The local Bivariate LISA analyses revealed that spatial autocorrelation of fire over time influences burning through fuel the clearing and regrowth of fuels. Large patches of Low-Low pixels in each comparison indicated that in each six year span the majority of pixels did not burn. Low burning pixels in the first 3 years surrounded by low burning pixels in the next 3 years is the highest occurring category of spatial autocorrelation in the study area. The spatial pattern of fire occurrence indicated by the original fire count data show that fire is more abundant in the western portion of the study area.

This pattern, however does not extend beyond the overall time-period of the count data. Rather, there were low burning periods (compared to the surrounding areas in the years before) throughout the western area in 2003-2005 and 2012-2014. The advantage of the Bivariate LISA data over counts binned by time period is that it shows spatial patterns and neighborhood affects. An important neighborhood affect observed was areas that burned at a high rate in the initial period were rarely surrounded by areas with a high rate in the lagged period. This is to be expected from pixel to pixel given fuel dynamics, and it also shows that large patches of similar burn trends result from spatial interactions. Fire was highly spatially auto correlated within time periods for both low-low and high-high, but in lagged time periods high-high was mostly absent because areas rarely burn highly in consecutive 3 year intervals. Importantly, Bivariate LISA shows that this goes beyond single pixels and hyperlocal fuel dynamics, surrounding neighbors in first and second orders affect fire occurrence in consecutive time periods. However, the proportion of high-high cells was far from uniform throughout the comparisons. There was a clear increase of high-high occurrences in the latest two comparisons by a magnitude of about 30,000 cells. This indicates a substantial change of fire return interval and change of how fire patch dynamics function over time. The expected pattern of low H-L, followed by high L-H, followed by low H-L, followed by high L-H is not present. Rather than the expected tradeoffs from consecutive comparisons there were similar situations in the first and fourth comparisons and second and third respectively. This reflected dynamic fire occurrence and burning patterns. From a management perspective, it can be concluded that fire regime in the region is influenced by neighboring fuels, which are influenced by fire. The temporal regrowth of fuel after fire in neighboring areas is an essential factor in fire regime patterns.

3.9 Regression Discussion

Modeling the drivers of fire occurrence is essential to understanding patterns of fire dynamics at large extents, but the applicability of these global models is spatially variable (Sá et al., 2011). Global models have been produced for southern African savannas (Parks et al., 2015) that seek to explain fire occurrence, but these models have limitations in the study area because they are based on data from controlled areas where applicable anthropogenic factors are not present and not incorporated into the model. Additionally, these models are often not applicable at the fine scale required to explain the high heterogeneity of vegetation characteristics over small areas in savanna systems. While it is difficult to model fire within a region using long term data it is essential for savanna management to enable an understanding of the patterns of vegetation structure. Regionally specific signs and magnitudes of well-known drivers are particularly important for regional fire dynamics.

In the global OLS and Poisson models, seasonality of precipitation, boreholes, and EVI had negative coefficients. Soil Moisture, Palmer Drought Severity Index (PDSI), and herbaceous cover had positive coefficients. The result of soil moisture and PDSI both having positive coefficients was unexpected. The expectation was that PDSI would have a negative effect because of less primary production in drought-prone areas, but the results imply that areas with long-term high soil moisture that also experience drought tend to burn. These dynamics suggest that vegetation production is enhanced by soil moisture and then prone to burning during times when the PDSI is high because of large amounts of dry fuel.

The other variables acted as expected regarding signs of coefficients. The borehole variable had a small magnitude implying that boreholes may have a week effect in the global models for the study area. Herbaceous cover is an aspect of fuel amount, so the positive relationship between the variable and fire was expected. The negative coefficient of EVI signifies that woody plants are likely contributing to greater EVI values so that in areas with high EVI there is less likely to be fire because of a higher woody plant to grass ratio.

The statistically global models provide singular coefficients for each explanatory variable influencing fire occurrence in the study area. The geographically weighted Poisson model allows for a spatially explicit exploration of where explanatory variables have statistical significance and the sign of the local coefficient. The analysis also provides ranges of local coefficients. All the variables had local coefficients that ranged from negative to positive which is an indication that there is a large amount of spatial heterogeneity in the study area. Herbaceous cover, EVI and seasonality of precipitant were mostly consistent in magnitude, and were significant across a considerable amount of space. The mean coefficients of the local variables reflect similar overall effects to the global models.

PDSI, EVI, and Herbaceous cover had high coverage of significant local coefficients. PDSI had the most variability of coefficients among the variables. Boreholes and precipitation seasonality had more significance in the Western portion of the study area than in the rest of the study area. EVI and temperature shared similar patterns of significance and signs of local coefficients. The northeast corner of the study had high positive coefficients for temperature and EVI, which is different than the rest of the study area. There are likely different factors affecting fire in the Northeast part of the study area. Observing the local coefficients spatially is helpful for identifying areas that do not perform as expected according to the spatial model. It is also apparent that spatial heterogeneity of variable coefficients limits the explanatory power of the global models.

3.10 Limitations

The main limitation to all the analyses performed is spatial resolution. The fire products used are at the scale of 500m, meaning that any patterns present at sub 500-meter scale are not accounted for. This limitation extends to the explanatory variables in the regression analyses as well. Another limitation to the models is the fact that long term variables are the focus rather than annual, intra-annual and sub-intra-annual affects. Regardless of these limitations, the analyses provide a furthered understanding of spatiotemporal fire dynamics in the study area.

3.11 Conclusion

Understanding coarse scale fire patterns at country and regional levels requires spatiotemporal analyses of both fire occurrence and the explanatory factors of fire occurrence (Touble et al., 2018). Bivariate LISA and seasonality analyses revealed a shift in burn seasonality and dynamic burn patterns in consecutive time periods. The Bivariate LISA analysis supported the hypothesis that fire occurrence over time is heavily affected by neighbors at the first and second levels. The increase of areas of high burning relative to the mean surrounded by areas of high burning relative to the mean in the following 3-year period indicates that fire regime may be changing in certain portions of the study area. The global regression model resulted in the expected signs and partial effects of the explanatory variables included. However, the relationship between fire and explanatory variables proved to be highly spatially variable.

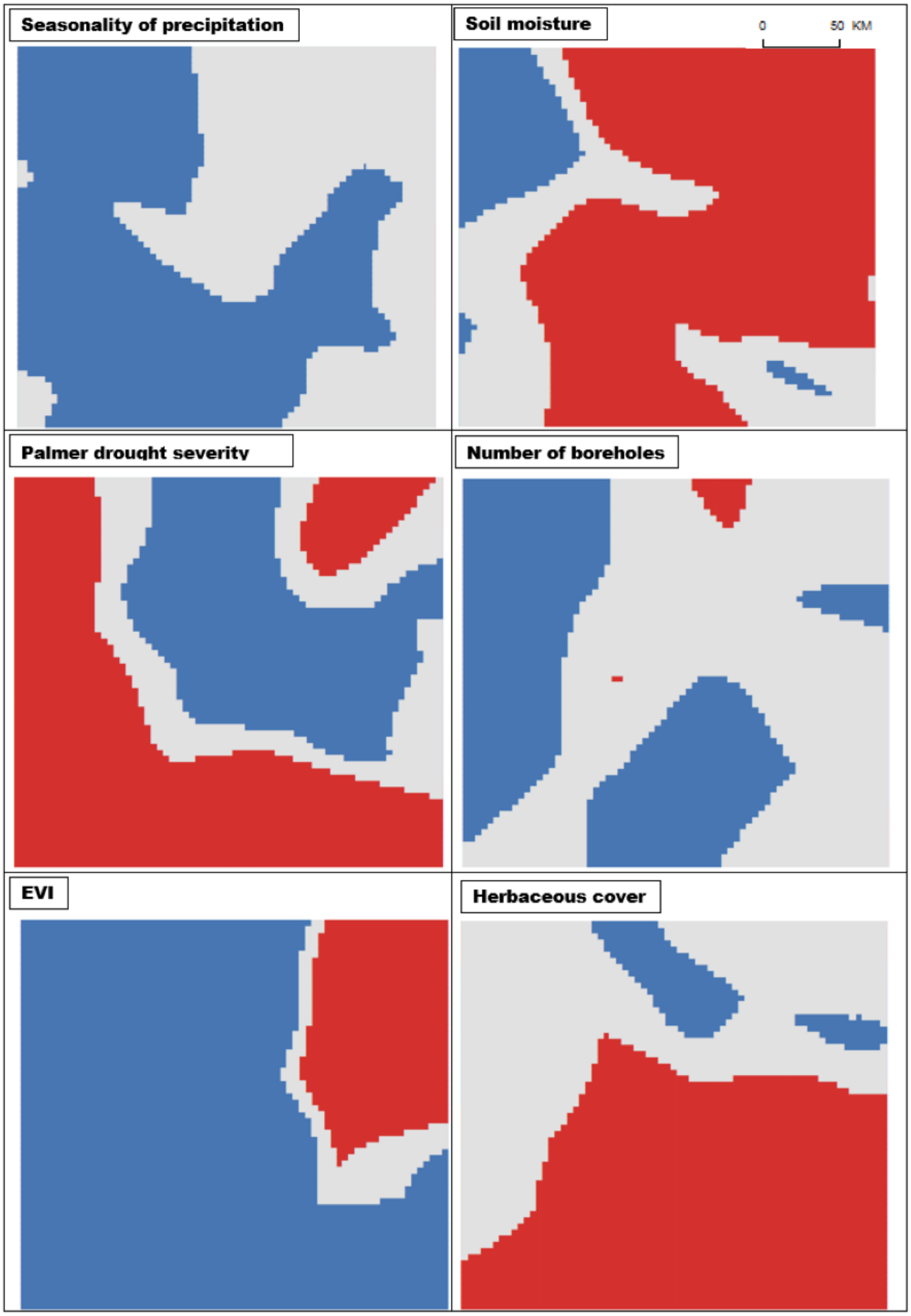

Figure 3.4: Maps with significant local coefficients– blue for negative and red for positivie

Chapter 4

Fine scale vegetation/fire modeling

4.1 Introduction

Remotely sensed savanna fire analyses are limited in the ability to reliably and accurately measure burn severity and vegetation response in savannas – specifically grass versus woody plant mortality and response, although burn severity measurements are improving with Lidar and radiometric methods (Meng et al. 2018, Bolton et al., 2015). In the absence of these often expensive and spatially/temporally limited data sources, detailed vegetation structure, morphology, and species data are difficult to obtain (Smit et al., 2016). These limitations lead to opportunities to enhance the understanding of the relationships between vegetation structure, morphology, and species (both grass and woody species) and how these relate to the intensity and characteristics of fire events (Case and Staver, 2016, Lehmann et al., 2014). Gains in these understandings in part depend on *in situ* methods to observe fine resolution fire and vegetation interactions.

In situ inputs greatly improves the ability for the dynamic vegetation types in the study area to be identified and classified (Mishra et al., 2014). *In situ* vegetation measurements provide accurate and detailed data that record grass and tree species, canopy cover, grass and tree biomass, and ground cover. The combination of these data with remotely sensed information provides present conditions on the ground to be compared to remotely sensed fire histories and vegetation conditions. Using measurements collected in the fieldwork study area, a grass biomass model was generated with independent variables – fire, distance from tar road, and woody cover. Following a fire event that burned two transects 2 months after measurements were made, measurements were taken 5 days after the fire to record post-burn mortality and fire magnitude. The resulting measurements and fuel scenarios were then used to compare biomass scenarios using a savanna fire model to project vegetation and fire dynamics in the future under conditions similar in grass/tree characteristics to the two transects.

These methods were employed in this thesis to observe the influences, interactions, and feedbacks between fire and savanna vegetation conditions, to test the following questions: 1) how are the vegetation conditions in the study area impacted by fire presence; 2) how do measured variables affect grass biomass in the study area; 3) how do vegetation conditions affect fire intensity and vegetation mortality; and 4) how do current vegetation conditions affect projected future vegetation conditions?

In situ ground cover data provides a fine resolution component to the coarse resolution component of the MODIS Burn Products discussed in chapter 3. Modeling vegetation response to fire history allows for testing the hypothesis that fire is an important factor in vegetation characteristics in the study area.

It also provides an opportunity to observe the influence of regional factors on fine-scale vegetation patterns.

In situ measured fire characteristics allows for an observation of fine resolution vegetation impact on fire and response to fire. Using these fine-scale observations in a long-term woody population model allows for a long-term prediction of woody-grass dynamics in the study area.

4.2 Vegetation Fieldwork Methods

Belt transects with square meter ground cover measurements were sampled along the transect. These methods were chosen to obtain three dimensional woody structure by measuring stems and canopies. Three dimensional measurements allow for canopy cover calculation and allometric equations to be applied to calculate woody plant biomass. Grass biomass was collected by cutting and measuring the grass in each ground cover square.

13- 100x2 meter, south facing, belt transects were sampled along 3 roads across the study area. Measurements were made from June 24th through June 29th, 2017. In each belt transect woody structural measurements were recorded – tree height, canopy height, middle canopy height, stem, and canopy dimensions on an X, Y grid, number of stems and DBH. Additionally, species of each individual tree were recorded. Each transect was separated by 10 km. The number of transects along each road reflects the length of each road. Transects were placed 100 meters away from the road to attempt to minimize the effects from the road, but for researcher's safety considering high large predator and elephant density in the field work study area plots were not placed further than 100 meters away from the road. 1X1 meter ground cover measurements, grass species identification, and grass biomass measurements were sampled at 25 meter increments along both sides of each transect. Wet, aboveground biomass was recorded on site.

Post burn measurements were recorded on October 1st, 2017 for two transects (R3T2 and R3T4) that burned on September 19th and 16th (respectively). Burn severity for woody plants and grass were calculated using the composite burn index developed by the USGS (Key and Benson, 1999). The post-burn measurements were recorded on October 1st, 2017.

The model used for projecting woody plant population was adapted from Higgins et al., 2000 and simulates savanna woody plant stem mortality, regrowth, establishment, and age in response to fire events in Southern Africa at a 1 hectare scale. Structurally, savannas are characterized by a mosaic comprised of a continuous grass layer and clumps of woody plants. The model is designed to test the effects of woody/grass balance on fire conditions and resulting woody plant mortality in a southern African savanna system with climatic characteristics like those of the study area.

The model was used in this thesis to project the number of woody plants in a savanna system over a period of regularly occurring fires under different fuel conditions. Precipitation, establishment, fuel moisture, relative humidity, wind, stem resprouting, and stem height are the state variables in the model. Fire intensity is a function of fuel moisture, humidity, wind speed, and grass standing crop. Grass standing crop was the variable of interest so it was the only variable different among the two sites tested. The initial state of the model is set with 100 individual woody plants. Discrete time incremental updates everything in parallel. Stochasticity is produced in each step from distributions (normal, Poisson, and exponential) that are produced using parameter means. A number is randomly selected from each of the distributions.

4.3 OLS Regression Variables

Table 4.1: Summary of variables used in the OLS regression

OLS VARIABLES	MEAN	STD. DEV.	MIN	MAX	VIF
CLIMATE					
MEAN MONTHLY PRECIP (MM)	29.11877	0.9298997	27.47	30.33	42.21
SEASONALITY OF PRECIPITATION (COEFFECIENT OF VARIAITON)	95.92308	1.336493	93	98	1.90
ANNAUL MEAN TEMPURATURE (C *10)	217.0769	1.393577	215	219	36.27
POPULATION AND GRAZING					
DISTANCE FROM BOREHOLE (METERS)	7146.352	3900.27	2296.38	1.53E+04	3.18
NUMBER OF BOREHOLES WITHIN 5 KM	0.6153846	0.92905	0	3	4.33
DISTANCE FROM ROAD (METERS)	20216.21	12103.59	2346.20	39527.20	3.66
FIRE					
BURNS SINCE 2010	0.3846154	0.7425958	0	2	2.71
BURNS SINCE 2000	1.538462	1.456667	0	4	5.21
VEGETATION					
WOODY CANOPY COVER (%)	8.051282	16.42053	0	85	1.24

Remotely sensed data were combined with *in situ* vegetation data to produce an OLS model testing the effects of fire, climate, population, grazing, and woody vegetation on aboveground grass biomass.

Grass biomass was measured in the field in 1 x 1-meter plots at 0, 50, and 100 meters along a belt transect where woody plant measurements occurred. Grasses were cut at the ground level and weighed in the field without drying, so the biomass measurements are not dry biomass. Visual estimates of greenness were recorded to estimate the effect of moisture on readings. Measurements occurred during the approximate middle of the dry season (early June) when most grasses were dry.

Canopy cover measurements are from structural measurements made in the 100 x 2-meter belt transect. Canopy cover percent was calculated by the division of total canopy area corrected for canopy overlap from the total area of the belt transect. The canopy cover measurements were used as a variable to test the effect of competition and woody/grass coexistence on grass biomass. Canopy cover

Google Earth Engine was used to acquire climate datasets for the OLS regression. Seasonality of precipitation and temperature are long-term historic climate data available from the WorldClim V1 Bioclim dataset (Hijmans et al. 2005). Seasonality is an important factor in savanna systems Temperature seasonality is measured with a standard deviation measurement multiplied by 100. Precipitation seasonality is measured by a coefficient of variation. Mean monthly precipitation, maximum annual temperature and soil moisture were acquired from TerraClimate monthly climate and climatic water balance for global terrestrial surfaces dataset that covers the time-period 2000 to present (Yu et al., 2016).

A human population grid is not applicable in the study area because it is a public rangeland. The variables accounting for anthropogenic impacts are number of boreholes within 5 km and distance from the tar road. Boreholes are human infrastructure that are often used as a proxy for grazing and general human land use (Moleele, 2002). Distance from the tar road represents multiple factors – permanent human population in Rakops and the surrounding area, the Boteti river, and an observed grazing density gradient from the road, river, and Rakops.

4.4 OLS Regression

An ordinary least squares regression (OLS) model was generated to test the factors affecting grass biomass. Grass biomass was tested because grass occurrence is a defining aspect of savanna vegetation. The factors selected include the influence of climate, fire, human population, grazing, and woody competition. The distance from road of each plot was more significant than borehole density as a domestic grazing variable. Beyond this simple grazing intensity gradient, grazing intensity is highly dynamic in the study area so it is important to note that the model does not fully explain grazing intensity. A log transformation was applied to grass biomass measurements to produce a normal distribution of data and residuals.

The variables for the models was tested for multicollinearity using a variance inflation factor test. The mean monthly precipitation and annual mean temperature had high values indicating multicollinearity between the two variables (32.57 and 26.96). Mean monthly precipitation was kept in the model because it is more likely to have small scale effects on grass biomass over the study area. The VIF test for the final model indicated low multicollinearity among the variables – monthly precipitation: 1.74, Seasonality of precipitation: 1.83, Distance from road: 1.74, burns since 2000: 2.04, canopy cover: 1.13.

For both models the residuals are normal and homogenous after using the log correction for grass biomass. A Shapiro-Wilk W test for normal data indicated a fairly high p-value for both models (0.2605, 0.2605) so the null hypothesis of normal data cannot be rejected. A Cameron and Trivedi's decomposition of IM-test which tests for heteroscedasticity indicated relative homogeneity of residuals for both models (0.3089, 0.0754).

4.5 Results

Grass biomass ranged from 250 to 2430 grams per square meter. Tree biomass ranged from 0 to 156.92 kilograms per plot. Number of grass species ranged from 2 to 8 per square meter. Number of woody species ranged from 0 to 8 per plot.

The OLS model that was prodeced explained 50 percent of grass biomass amount in the study area (Table 4.2). The model yielded high significance for canopy cover, number of burns since 2000, and distance from road. Woody canopy cover percentage had a negative coefficient. Burns since 2000 had a high magnitude positive coefficient. Distance from the tar road had a positive coefficient. Climate factors and borehole distribution were insignificant in both models.

Table 4.2: Results from the OLS model testing the influence of fire, woody competition, grazing, anthropogenic factors, and climate on grass biomass

Burns since 2000 Grass Biomass OLS Model	Adj. R^2: 0.5045				
	Coefficient	Standard Error	t	P>|t|	VIF
Woody	-0.0121511	0.00463	-2.62	0.011	1.13
Burns since 2000	0.2089043	0.0700427	2.98	0.004	2.04
Distance from road	0.0000264	7.81E-06	3.38	0.001	1.74
Precipitation Coefficient of Variation	0.0092644	0.073427	0.13	0.9	1.83
Precipitation	0.057632	0.1017925	0.57	0.573	1.74
Boreholes within 5km	-0.1074912	0.0920446	-1.17	0.247	1.43
_cons	1.578949	5.958681	0.26	0.792	

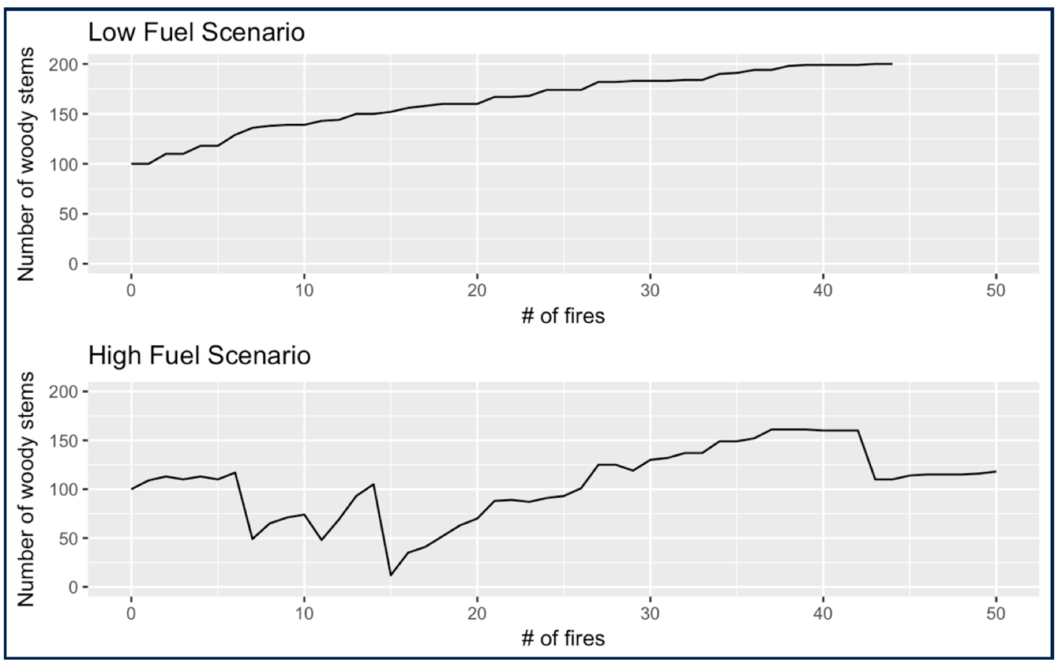

Figure 4.1: Projected woody plant population over 50 fire events in divergent fuel scenarios

The two plots that burned had contrasting vegetation conditions in the pre-burn measurements (Table 4.2). Burned plot 1 had a high amount of grass biomass while burned plot 2 had a low amount of grass biomass. Woody plant biomass was high in burned plot 2– 140 kg. Woody plant biomass was relatively low in burned plot 1–73.522. Burned plot 1 had past fires in 2000 and 2006, while burned plot 2 had no fire events since 2000 prior to the 2017 fire. The fire magnitudes and immediate vegetation mortalities reflected the contrasting vegetation conditions. The understory intensity of the burned plot 1 measured 18 with the composite burn index reflecting high amounts of aboveground grass burnt, while the understory intensity of burned plot 2 measured 7 reflecting less aboveground grass burnt. Overstory intensity in burn plot 1 was high–18, with large amounts of woody plant mortality. Burn plot 2 overstory intensity measured 0 signaling that mature woody plants were unaffected by the fire.

Repeated burns with the same fuel scenarios of the two burned plots result in very disparate projections of woody plant populations. In conditions under the low fuel scenario it is projected that the woody plant population will grow until closed canopy conditions exist. In other words, even if regular fires continue under the same vegetation conditions there will be continued woody plant encroachment. In the high fuel scenario (observed at burn plot 1) the woody plant population remains stable with regular fires.

4.6 Discussion

Based on the analyses done here, key variables affecting the amount of grass biomass included fire, grazing, and woody/grass dynamics. Pre-and post-fire vegetation analyses indicated that fire intensity and immediate veg-

Burned Plot 1 *Composite Burn Index

Understory Intensity	18
Over story Intensity	11
Total	29

Tree Biomass before burn: 73.522 kg
Grass Biomass before burn: 980 grams
Number of burns since 2000: 2 (2000, 2006)

Burned Plot 2

Understory Intensity	7
Over story Intensity	0
Total	7

Tree Biomass before burn: 140 kg
Grass Biomass before burn: 450 grams
Number of burns since 2000: 0

Figure 4.2: Results from the composite burn index show disparate fire conditions in the two plots

etation mortality were heavily influenced by pre-burn vegetation conditions in the study area meaning that fine scale vegetation differences influence fire conditions through fuel characteristics.

Climate variables in the models were insignificant, which suggests that climate variation over that extent may not be enough to influence grass biomass differences among the plots. The observed positive relationship between distance from the tar road and grass biomass likely reflects higher domestic grazing and browsing density closer to the tar road, but the grazing density/grass biomass relationship in the study area is more complex given that borehole density – a common proxy method for grazing density – had a negative coefficient, but was not statistically significant. Heavy grazing density (at a rate where no woody plants are present) was observed at a buffer of approximately 10 km from the tar-road. The model did not account for wild grazing and browsing which adds further complexity. Despite these challenges, the r squared value and F value suggest that variables included explain a large amount of vegetation conditions observed.

Woody plant canopy cover has a negative relationship with grass biomass. The negative relationship is expected given resource competition dynamics between woody cover and grass (Ketter and Holdo, 2018). However this relationship is not necessarily limited to one direction given that it is not known at what rate canopy cover begins to outcompete and reduce grasses in the area (Venter et al., 2018).

The results of the measured fire severity and vegetation response within the study area illustrate that fire conditions range very widely in the study area. In this case, the two burned plots varied greatly in intensity and vegetation mortality even though the plots burned on the same day and were 20 km apart in location. The differences in vegetation conditions before the fire likely had a large effect on the burn conditions and resulting vegetation mortality. This highlights a key point–that fire histories influence vegetation dynamics which determine how a given area will burn. A feedback of fire and fuel conditions exists where past fires influence grass biomass as observed with the OLS model and grass biomass influences how and if an area will burn.

The model projection of woody plant populations through multiple burns shown in figure 4.1 indicates that over a number of fires vegetation conditions greatly influence woody plant population size. These projections indicate that even with burn occurrence, conditions where woody cover is outcompeting grass leading to low grass biomass, fire alone may not change woody/grass ratio. It also implies that fine scale fuel conditions across the study area impact broader patterns of vegetation.

Further research should focus on identifying thresholds where fire presence will no longer cause woody plant mortality and where encroachment creates a negative feedback with fire.

Chapter 5

Conclusion

5.1 Introduction

Grass-tree coexistence is a defining characteristic of savanna ecosystems where a continuous grass mosaic provides resources for grazing species, and patches of woody plants provide resources for browsing species (Scholes and Archer, 1997). Livestock and wildlife depend on savanna systems and the processes that contribute to system defining grass-tree coexistence (Fynn et al., 2016). A variety of factors affect vegetation in savannas in multidirectional processes and feedbacks. The factors are climate, grazing, and fire, which all interact (Lehsten et al., 2016). Understanding how these factors influence vegetation in savanna systems is imperative to maintaining savanna function and the socioeconomic and wildlife systems that depend on it while anthropogenic global change causes novel climate and land use scenarios (Franklin et al., 2016; Staver et al., 2011; Stevens et al., 2017).

The complex dynamics of savanna vegetation across traditional vegetation plot sizes (100-1000 meters) create a fundamental challenge in understanding large scale patterns of savanna dynamics because limitations in plot sizes offer small samples of tree distributions and these patterns are influenced by spatial self organization of trees (Staver, 2018). Fire is a key contributing factor to the complexity in savanna vegetation systems (Touboul et al., 2018). It has been well documented that small scale patterns of fire in savanna systems impacts patterns of fire over large areas, but little is known about how processes at larger extents and scales affect local fire presence and how factors that affect fire occurrence vary over space (Schertzer et al., 2015).

Prior to the introduction of multispectral satellite remote sensing, fire had been difficult to observe over large spatial extents and temporal periods (Lentile et al., 2006). Remotely sensed data now exists with enough temporal coverage to observe recent fire history in savannas where fire return is relatively frequent (Mayr et al., 2018). With the diversity of sensors, products, and software currently available, savanna fire dynamics can be monitored and observed over many spatial and temporal scales as well as spatial extents (Hantson et al., 2016). However, the affect that these different extents and scales have on findings, and the ability of multiple scales to inform different levels of management is not well understood.

This work contributes a multi-scale approach that uses remote sensing and *in situ* measurements to test the hypothesis that fire and vegetation patterns interact via distinct processes at different extents and resolutions in a southern African savanna system.

The savanna biome within southern Africa includes savannas across diverse climate conditions that encompass vast areas containing sizable populations of livestock and some of the earth's largest remaining terrestrial wildlife habitats. The maintenance of populations of livestock and wildlife are highly dependent on grazing resources, meaning that changes in grass amount and quality for grazing have a strong human impact (O'Connor et al., 2014). The area is also a mosaic of conservation, communal, and commercial land uses, all of which experience different dynamics of the factors discussed earlier in this review. Conservation land uses are vitally important to the national and international economies (Snyman, 2012). This part of the African continent is home to vast protected savannas of conservation importance, including the Central Kalahari Game Reserve, Etosha National Park, and Kruger National Park. In addition, the area is home to the world's highest diversity of wild ungulate species (Toit and Cumming, 1999), as well as some of world's last remaining hotspots of top predators and megafauna (Mali et al., 2016). Outside of conservation areas, livestock grazing dominates savanna ecosystems where pastoral communities depend on grazing for livelihoods and food security (Ward, 2005).

The unique configuration of wild grazing and browsing ungulates provide a variety of grazing effects that are specific to African savannas. Mechanistically, grazing pressure decreases fuel load, which in turn, decreases fire intensity and woody plant mortality (Fuhlendorf et al., 2009). Populations of browsers actually have the opposite effect on woody plant mortality through their direct consumption of material from woody trees. This has been found to lead to more grass growth and more intense fires (van Langevelde et al., 2003). Given the populations of large wild browsers on the African continent such as elephants and giraffes it could be argued that the impact of woody encroachment suppression from browsers represents a regional phenomenon. However, it may also be represented as a local phenomenon that differentially affects parts of the savanna due to high spatial heterogeneity in wild browser occurrence, driven by differences in land use and climate.

The effects of wild grazers and browsers on woody encroachment are most evident in Africa's protected areas. Increased woody cover in Kruger National Park was associated with reduced grass biomass and fire frequency (Smit and Prins, 2015). This reduction of grass biomass has resulted in a distinct change in the herbivore communities that can be sustained in the area. Though the total number of herbivore species stayed the same overall within Kruger, there was an increase in overall biomass of browser species and a corresponding decrease in grazing species (Smit and Prins, 2015).

The focus on national parks of economic importance in regions that have records of previous studies has meant that there are geographic differences of which savannas are studied even within southern Africa. The savannas of Botswana serve as a prime example. Little is known about fire regimes–spatially and temporally–through much of the country. Contributing to this gap in knowledge are complex systems of domestic and wild grazing, in which little is known about density and comprehensive measurements have been few and far between. Furthermore, land management is conducted at a multitude of extents within a mosaic of communal and private ranching areas and conservation land uses (Dougill et al., 2016). Interactions of burning and grazing likely drive the patterns and processes of savanna systems over much of the country, as has been documented in many others. However, the variables affecting burning and grazing patterns include climate, land use, human population pressures, fire history, and land use history trajectories (Hantson et al., 2015). The interactions of these variables vary over space, and depending on the scale of analysis, may be more or less relevant. For example, within a fine scale, the land use type may be communal over the entire area, so the grazing patterns of individual households may be most relevant. However, at an extent of the entire country, the land use is highly pertinent, but the impact of individual households' grazing patterns is probably obscured by other factors.

A direct investigation of grazing intensity in south-eastern Botswana provides powerful evidence that grazing intensity is an important factor of vegetation dynamics in the region at this scale (Moleele and Perkins, 1998). Among variables that statistically explained increased woody cover – cattle density, soil nitrogen, distance from borehole, and tree cover– cattle density was the highest by a wide margin. As previously noted, grazing intensity impacts woody cover through decreased fire intensity via the removal of fuel (Roques et al. 2001). This grazing either excludes fire events or significantly decreases mortality rate of woody tree species during fire events. Though this analysis provides strong results for a specific driver, the study was conducted in a specific region at a particular scale.

5.2 Summary

Fire is a key aspect of savanna ecosystems that affects savanna vegetation in multidirectional ways across numerous spatial and temporal scales (Higgins et al., 2000; Lehmann et al., 2014; Touboul et al., 2018). The drivers, feedbacks, interactions, and processes that affect fire occurrence and intensity also function across scales and directions (Trauernicht et al., 2015; Aleman and Staver, 2018). These complexities have made it a challenge to understand fire's role in savanna vegetation dyanmics. An extensive debate within the savanna ecology literature centers on the process or set of processes that contribute to grass-tree coexistence and functioning savanna systems (Sankaran et al., 2008; Schertzer et al., 2015; Thomas et al., 2018). It is clear from the decades of savanna ecology and woody encroachment literature that fire plays a crucial role in grass-tree coexistence and that fire suppression via direct suppression and domestic grazing is an important factor of woody plant encroachment (D'Odorico et al., 2006; Stevens et al., 2018). This has led to a multitude of studies aiming to observe and analyze the coarse scale patterns of fire occurrence and trends (Asner et al., 2004; Bond et al., 2005; Stevens et al., 2017). An underdeveloped aspect of the literature is the direct consideration of the interactions of fire and vegetation at multiple scales and how scale influences findings and the relevance of findings for savanna management and policy. The analyses performed here varied in spatial and temporal scale and together show the multiscale nature of savanna fire dynamics as well as the different findings and level of nuance at each scale.

5.3 Country Scale analyses

Remotely sensed data from MCD64A1 (500m) (Giglio et al., 2015) was compiled using Google Earth Engine to form an 18-year fire history for Botswana. Seasonality of fire was observed using MCD14DL (1000m) by plotting number of burned pixels at day of year for every year from 2000 to 2009, and 2010 to 2018. When observed at the country scale fire patterns are visibly influenced by precipitation gradients and land use. Almost the entire extent of the Central Kalahari Game Reserve has burned since 2000, and most areas have burned several times. There is a distinct fire season in Botswana occurring virtually exclusively in the dry season when lightning strikes are rare, suggesting that most ignition sources are anthropogenic. Seasonally, there was an observed increase in late season burning in the later time period.

5.4 Regional Scale analyses

Fuel connectivity is a determinant of if and where a fire will spread (e.g. fire breaks) (Kahiu, 2018). The use of Bivariate LISA was a novel method to explore fuel connectivity by measuring the spatial autocorrelation of fire in two separate time periods. At the Kalahari scale, the spatiotemporal interactions of fire were explored using Bivariate Local Moran's I (Bivariate LISA). The findings from the analysis confirm that fire occurrence is influenced spatially by past occurrence and reoccurrence follows a spatial and temporal pattern. Furthermore, bivariate LISA allowed these dynamics to be classified and measured. The high number of significant pixels indicates that fire occurrence in the initial three-year period affected fire occurrence in neighboring 500 meter pixels in the following three-year period for each of the four time-period comparisons. From 2000-2009 there were a total of 1,614 high-high cells. From 2009-2014 there were 40,951. The high-high cell regions had enough post burn fuel accumulation within a six-year or less period to provide fuel connectivity for fire return. The notable increase of high-high cells in the later half of the analysis time frame signals that there was a change in fire regime in a significant number of cells. It is unknown at this point whether it is the start of a trend, cyclical, or unique. There was a high amount of high-low and low-high cells throughout, indicating that for most of the area that burned in initial periods, post burn fuel connectivity limited fire return within 6 years. There were large regions that remained low-low from 2000-2014. Within these regions there are likely fire breaks that function over large extents. This is a promising method for observing fuel connectivity over time, which has been identified as a key issue across savannas (Archibald et al., 2009). These dynamics can be tested across climates and land uses to see how these dynamics change with different conditions.

Beyond the effect that previous fires have on fire occurrence, it is important to investigate the other variables that affect burning. Although variables effecting fire occurrence patterns can be observed through global statistics at various spatial extents, it is difficult to manage fire across large extents because land use varies heavily and local interactions of human infrastructure, vegetation, and grazing all affect fire (Wigley et al., 2010). Geographically weighted regression (GWR) assigns local coefficients (per pixel) so that spatial variation of variables can be observed (Brunsdon et al., 1998). Geographically weighted regression of variables affecting fire occurrence has been performed for the continent of Africa, but local coefficients were insignificant across Botswana because fire occurrence was drowned out by larger rates of fire in the tropical regions (Saét al., 2011). The GWR model showed that the relationship between fire occurrence and explanatory variables were highly spatially variable in the Botswana Kalahari region. Boreholes, and EVI were mostly negative, but had some local positive coefficients. Herbaceous cover had the highest amount of local positive coefficients of any variable. Drought severity index had the most variation of positive and negative coefficients. Seasonality of precipitation was the only variable with significant local coefficients of one sign only (negative). The coarse scale analyses of spatial autocorrelation and fire seasonality offer effective methods of identifying areas of interest in terms of fire management, but given the spatial variation of important variables observed in the GWR, actual management strategies must account for locally specific dynamics.

5.5 Local Scale analyses

The second chapter in the analysis focused on local fire dynamics in an area where there are heterogeneous vegetation conditions despite relative homogeneity of precipitation, soil, and elevation. This is an example of a region that is difficult to account for at coarse scales because of highly heterogeneous grazing densities. *In situ* vegetation measurements provided accurate and detailed grass and woody plant data that were used to produce a grass biomass model. Grass biomass was used as a dependent variable because increasing and maintaining grass biomass is usually a central component of savanna management (Wilcox et al., 2018). The OLS model for the *in situ* vegetation study area showed that fire occurrence (particularly within the past 10 years) is statistically significant and positively correlated with grass biomass. Woody plant cover was statistically significant and negatively correlated with grass biomass. Distance from the anthropogenic features (tar road, river, and nearest town) was included to capture the effect of grazing density, and was significant and positively correlated with grass biomass. Boreholes – a common grazing density proxy variable, particularly in Botswana (Dougill et al., 2016) – was not significant in the model. The effective anthropogenic grazing variable in the model was locally specific, however if the model covered a larger extent the Central Kalahari Game Reserve would be included and distance from the anthropogenic features would be inapplicable inside the reserve because there is virtually no domestic grazing in the reserve (Selebatso et al., 2018). The Rsquared value was 0.5344 using burns since 2010, and 0.5045 using burns since 2000. Overall, these findings highlight the influences of fire, grass-tree interactions, and human land use dynamics on grass biomass at fine scales. Locally specific anthropogenic contexts need to be included to affectively understand local savanna dynamics. Evidently vegetation conditions are influenced by fire presence in the vegetation study area. Fire intensity also needs be considered because intensity of fire affects and is affected by vegetation conditions (Laris et al., 2017).

Post burn *in situ* measurements provided nuanced detail that showed vastly different burning conditions and vegetation mortality rates. The fire characteristics of the two plots – despite very similar temperature, moisture level and, wind conditions at time of burn – varied widely. This level of heterogeneity over a relatively small distance in similar conditions shows the limitations of fire presence and seasonality in explaining vegetation conditions. The feedback of vegetation and fire – heterogeneous vegetation conditions causing heterogeneous fire conditions, causing heterogeneous vegetation response to fire – is a key variable in complex vegetation composition in the study area. The long-term consequences of these feedbacks were modeled and showed that vastly disparate conditions result from regular burning at distinct and consistent fuel conditions. The nature of these feedbacks over time is a key determinate in woody/grass ratio. In many cases, fire presence alone has been discussed in savannas without a focus on fire intensity (Luo et al., 2017), but the fire intensity and projection analyses support the hypothesis that fire intensity may ultimately have an equal or greater role on grass-tree coexistence than presence. This depends on the assumption that low intensity fires lead to future low intensity fires and high intensity fires lead to future high intensity fires. There is some support for this (Smit et al., 2016), but more empirical work is needed on this subject.

5.6 Limitations

A key limitation in the combination of remotely sensed fire data with *in situ* vegetation measurements is spatial scale (Bradley, 2014). The MODIS fire product used to determine fire history is 500m resolution meaning that there is a level of uncertainty when working at a plot level that is 100m. This is especially apparent given the heterogeneity of fire conditions observed within the fieldwork study area. Despite this scale mismatch, MODIS fire data were highly significant and influential in the grass biomass model. Across the savanna biome and especially within the analyses performed in this research there is a severe lack of understanding of grazing densities in open rangelands (Fetzel et al., 2017). Additionally, little is known about how shared human/wildlife grazing and browsing systems function regarding grazing and browsing intensity and how these influences affect grass-tree coexistence as well as fire (Neilly et al., 2016). To provide more strongly applicable findings for small-scale rangeland managers a more holistic and precise picture of grazing and browsing intensity is needed along with, specifically in the vegetation study area of this project, how these dynamics influence wildlife and how wildlife affects grazing/browsing intensity. In rangelands where cattle ownership is fluid and fences do not delineate areas of ownership, it is a challenge to study livestock density and wildlife density, especially when the game reserve abutting the study area causes a likely fluid dynamic of wild browsers and grazers.

Critical differences between study scales include the high magnitude of influence of climate in coarse scale models, while at the fine scale, climatic differences over the local study area did not influence grass biomass. These scale dynamics support the idea that climate variables and climate change are essential variables at the policy level, where fire may be difficult to manage, given complexities in land use, ignition sources, and high heterogeneity in vegetation and burn conditions. At the policy level, a relevant fire variable is spatial autocorrelation over time of fire occurrence. Patterns exist across land uses of influence neighboring areas on the previous burning on fire return. While this is a critical observation at the policy level, the full complexity of local fire, grazing patterns, and heterogeneity of vegetation conditions show that fire management requires a fine scale component. At the local level, climate is less relevant for differentiating grass biomass conditions, even in an area with heterogeneous rainfall patterns that is right at the cutoff of water/nutrient limitation.

Short term weather conditions have a large influence on fire occurrence and intensity (Bedia et al., 2015), modeling fire occurrence and fire intensity over multiple years makes it so that weather conditions are challenging to incorporate (Abatzoglou et al., 2018). The incorporation of long-term climate with short-term weather in fire models is a key step to understanding savanna fire dynamics. Particularly questions including if singular weather events change fuel characteristic feedbacks. Additionally, ignition locations are influential to fire occurrence, but are hard to incorporate into long term models (Benali et al., 2016). The influence of ignition locations on fire occurrence over time requires locally applicable context, similar to the anthropogenic features in the vegetation study area OLS model.

5.7 Discussion and further studies

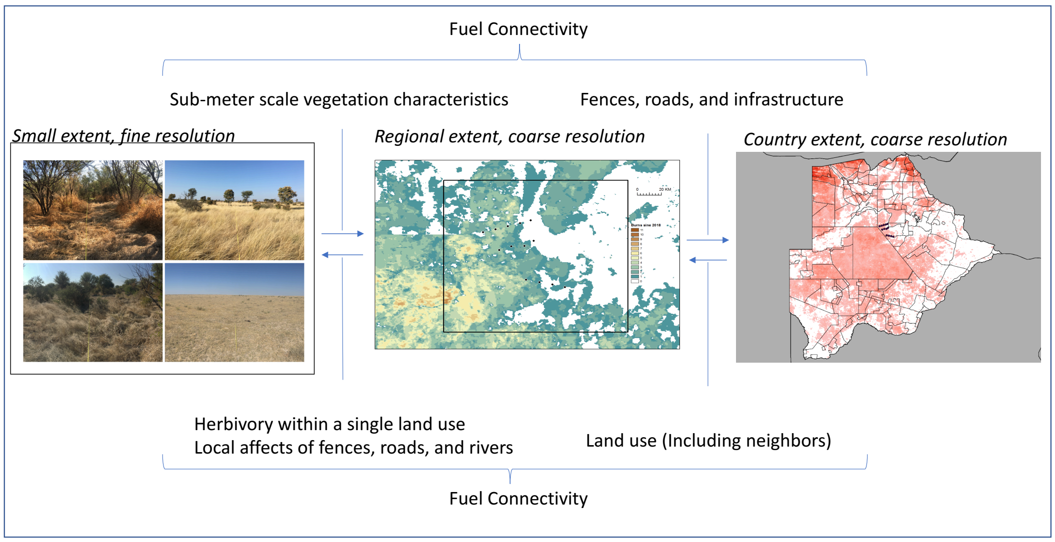

Figure 5.1: Fuel Connectivity is a critical factor at a variety of extents and resolutions

The coarse scale analyses performed in this study are policy relevant while the fine scale analyses are management relevant. The Botswana Kalahari has heterogeneous vegetation conditions that interact with fire in complex ways over time and space. To understand these complexities remotely sensed fire analyses are not sufficient alone, but are a vital component in understanding coarse spatial scale and temporal patterns. As technological advances continue with regards to remote sensing it is imperative that savanna fire analyses take scale into account both in terms of methodology and in applicability of findings. *In situ* fine scale analyses continue to offer important information, and must continue to inform and contextualize coarse scale findings. The interactions between the coarse scale neighborhood dynamics and the fine scale vegetation conditions of savanna fire are key to the functioning of global savanna systems and woody encroachment.

The main findings from the analyses are that land use, herbivory, human population, and infrastructure affect patterns of fire occurrence and intensity at multiple extents and resolutions, through spatial and temporal fuel connectivity. Diverse land uses in neighboring areas – Central Kalahari Game Reserve to the southwest, ranches to the west/northwest, national parks to the northeast, and pastoral to the east/southeast– contribute to heterogeneous fire patterns in the study area via spatial influence of fuel connectivity and fire return over time observed in the Bivariate Local Moran's I analysis. Regionally variable past fire presence and herbivory also influence local grass-tree balance observed in the grass biomass OLS model. The small-scale fuel connectivity dynamics influence larger fire patterns because small fuel breaks influence where fire will spread. The importance of these fuel dynamics was observed in the geographically weighted regression analysis with the EVI and herbaceous cover variables.Variability in fire intensity is caused by and contributes to heterogeneous vegetation conditions that was observed by the fire intensity measurements and woody plant population models.

There are opportunities for further studies to test fire impacts from large extents and surrounding areas, develop longer and more detailed fire histories, and test the role of fire occurrence and intensity in encouraging fire return. Further studies should test the hypothesis that savannas located within and surrounded by diverse sets of land uses experience spatially and temporally diverse fire conditions leading to heterogeneous vegetation conditions, while savannas existing within a more uniform set of land uses experience more uniform spatial and temporal fire dynamics which encourage uniform vegetation conditions. This hypothesis needs to be tested across climate conditions and different kinds and magnitudes of vegetation heterogeneity.

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